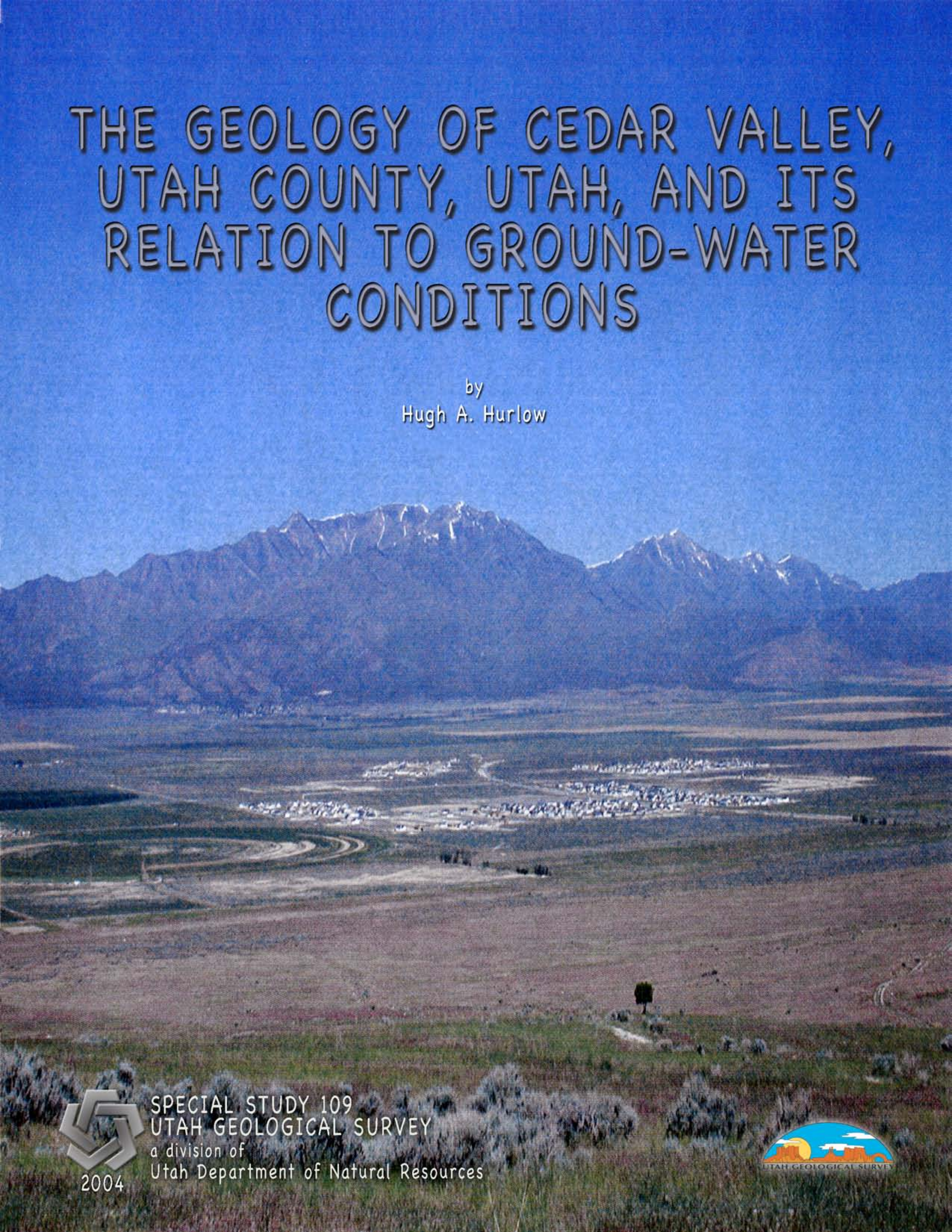
THE GEOLOGY OF CEDAR VALLEY, UTAH COUNTY, UTAH, AND ITS RELATION TO GROUND-WATER CONDITIONS

by
Hugh A. Hurlow



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Cover Photo: View to the northwest of north-central Cedar Valley, with the town of Eagle Mountain in the foreground and the southern Oquirrh Mountains in the background. Photo by author.

ISBN 1-55791-701-9

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THE GEOLOGY OF CEDAR VALLEY, UTAH COUNTY, UTAH, AND ITS RELATION TO GROUND-WATER CONDITIONS

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ABSTRACT

Cedar Valley, Utah County, Utah, is a Quaternary-Tertiary-age structural basin in the Utah Lake hydrologic basin of the northeastern Great Basin. The principal aquifers in the Cedar Valley drainage basin are Quaternary to Tertiary basin-fill sediments and Paleozoic bedrock composed of interlayered carbonate and quartzite. Development of ground water in bedrock aquifers has increased substantially in recent years due to population increases in northeastern Cedar Valley related to rapid growth in the Wasatch Front urban area.

Recharge to the Cedar Valley ground-water system occurs principally by infiltration of precipitation and snowmelt to bedrock in the southern Oquirrh Mountains on the northwestern valley margin; this water percolates through bedrock and enters the basin fill along the base of the mountains. Ground water exits the Cedar Valley drainage basin eastward by subsurface outflow within bedrock below Cedar Pass and the Mosida Hills, which bound the northeastern and southeastern parts of Cedar Valley, respectively.

Cedar Valley is within the Idaho-Wyoming-Utah salient of the Sevier orogen of Mesozoic to early Tertiary age, and in the eastern part of the late Tertiary Basin and Range Province. Pre-Tertiary bedrock was deformed into large folds and cut by thrust faults during the Sevier orogeny. During early to middle Tertiary time, thick volcanic deposits were deposited in the study area; their source areas were just north and south of the study area boundary. Steeply dipping, Miocene to mid-Quaternary-age Basin and Range normal faults cut pre-existing structures of the fold and thrust belt and the middle Tertiary volcanic deposits, defining the present-day topography. Cedar Valley formed as a north-trending graben, bound on either side by normal faults that dropped the basin center down. Up to 2,000 feet (600 m) of basin-fill sediment accumulated in this structural depression. Beginning in Quaternary time, lakes occupied Cedar Valley during times of high precipitation and glacial advances. Much of the basin fill, therefore, consists of lakebed deposits in the central part of the valley, grading to and interbedded with alluvial-fan deposits along the valley margins.

Ground water in the basin-fill aquifer is unconfined in the alluvial fans along the valley margins, and confined in the transition zone between alluvial-fan and lakebed deposits and in the valley center. Fairfield Spring, an important water-supply source for domestic and irrigation use, issues from the toe of a major alluvial fan in the west-central part of the valley. Hydrologic communication between Fairfield Spring and two irrigation wells located 2 miles (3 km) to the north-northwest is due to strong hydrologic communication along either a subsurface fault or a sharp change in hydraulic conductivity at a facies change coinciding with the distal margin of the alluvial fan.

Total-dissolved-solids concentrations in Cedar Valley ground water are typically less than 1,000 mg/L, nitrate concentrations (except for one privately owned well) are less than 10 mg/L, and no other chemical constituents exceed U.S. Environmental Protection Agency standards for drinking water. Ground water along the northeastern margin of Cedar Valley has total-dissolved-solids concentrations ranging from about 400 to 1,200 mg/L and is enriched in sodium and chloride relative to the northwestern part of the valley. The change in ground-water chemistry is due to mixing with water ascending along the Lake Mountains fault on the eastern boundary of Cedar Valley. Ground water in southeastern Cedar Valley has moderate to high salinity and sodium hazard, total-dissolved-solids from about 1,700 to 2,000 mg/L, and is enriched in sodium and sulfate relative to ground water in the northeastern part of the valley. Chemical reactions between the ground water and clay-rich, sulfide-bearing sediment of Lake Bonneville, the Tertiary Salt Lake Formation, and/or with Oligocene tuff are the likely cause for this degradation of ground-water quality.

Bedrock aquifers include Tertiary volcanic rocks, upper and lower Paleozoic carbonate strata, and lower Paleozoic quartzite. The Tertiary Salt Lake Formation, the Mississippian-Pennsylvanian Manning Canyon Shale, the middle member of the Mississippian Great Blue Limestone, and the lower part of the middle Paleozoic carbonate sequence form aquitards.

Joints in bedrock aquifers facilitate ground-water flow.

Joints in layered sedimentary rocks typically include two sets perpendicular to bedding and one bedding-parallel set. In the upper Paleozoic rocks, joints parallel to bedding planes combined with interlayering of low-permeability mudstone result in preferred ground-water flow parallel to bedding planes.

Folds and faults also influence ground-water flow in bedrock aquifers. Increased fracture density enhances ground-water transport parallel to anticlinal fold axes. The east-dipping limb of the Lake Mountains syncline guides ground water away from Cedar Valley and toward the hinge line of the fold, where it likely flows to the north and south into the Utah Lake drainage basin. Most faults in the study area likely form barriers to ground-water flow across their planes, and high joint density adjacent to some faults may enhance fault-parallel flow.

Flow of ground water from aquifers underlying the Cedar Valley drainage basin to western Utah Lake and the Jordan River likely occurs below the Cedar Pass and Mosida Hills areas, as hypothesized by previous workers. Ground-water flow in bedrock aquifers in these two areas is generally eastward, as determined by regional hydraulic gradients, but local flow patterns are likely complex.

INTRODUCTION

The Cedar Valley surface-drainage area forms the western part of the Utah Lake hydrologic basin (figure 1), in the northeastern Great Basin (Eakin and others, 1976). Cedar Valley lies between the southern Oquirrh Mountains and Utah Lake, which comprise important recharge and discharge areas, respectively, in the Utah Lake basin (figures 2 and 3). Population growth and expansion of the Wasatch Front urban area, about 20 miles (32 km) east of Cedar Valley, has caused a rapid increase in residential development in northern Cedar Valley in recent years. The establishment of Eagle Mountain City in the northeastern part of the valley and population increases in the towns of Cedar Fort and Fairfield exemplify this growth. The Utah Governor's Office of Planning and Budget (2002) estimated that the population of Eagle Mountain City alone will exceed 20,000 by the year 2030, whereas the present population of northern Cedar Valley is about 2,500.

The increase in water use expected to accompany this population growth is roughly 25 percent of the estimated annual water available for recharge to ground-water reservoirs below Cedar Valley: Feltis (1967) estimated that about 24,000 acre-feet (30 hm^3) of water recharge the Cedar Valley hydrologic system annually, whereas a population increase of 20,000 will result in increased demand of about 6,000 acre-feet (7 hm^3) per year, based on average use in Utah Lake basin of 272 gallons (1,030 L) per capita per day (Utah Division of Water Resources, 2001, p. 23). If increased ground-water withdrawals from within the Cedar Valley drainage basin are used to meet this increased demand, the long-term impact on the Cedar Valley hydrologic system may be substantial. Water-supply issues in the Utah Lake drainage basin may also be affected, because ground water flows from Cedar Valley to western Utah Lake in bedrock in the subsurface (Feltis, 1967; Dustin and Merritt, 1980).

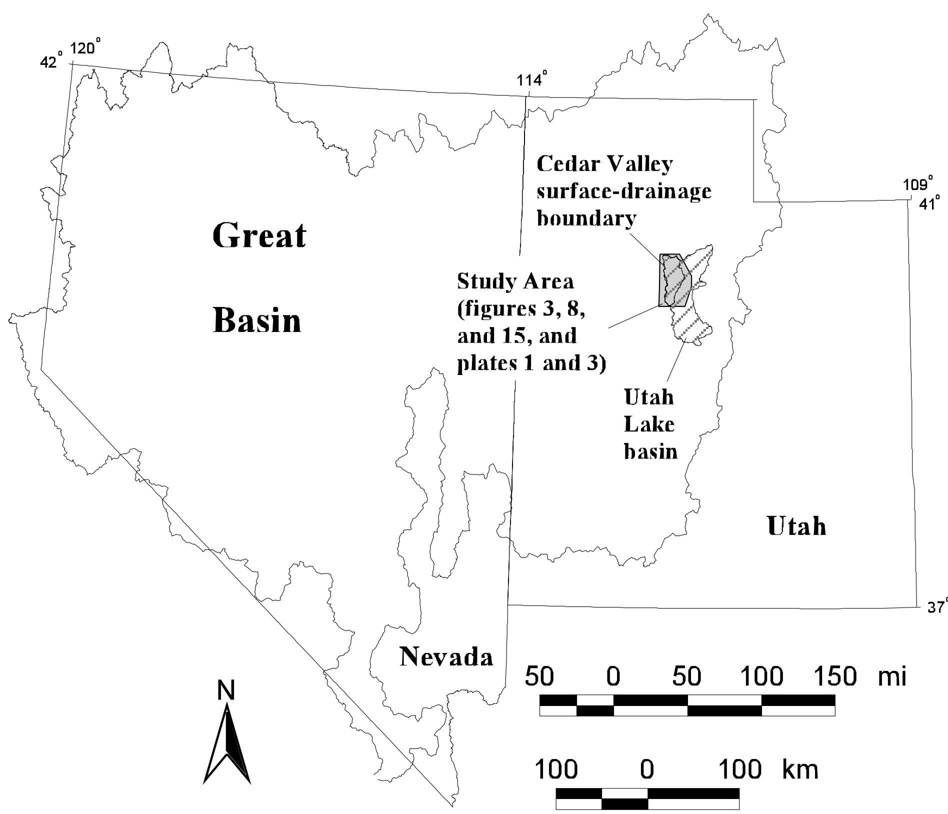

Figure 1. *Location of Cedar Valley, Utah County, study area within the Great Basin and Utah Lake basin.*

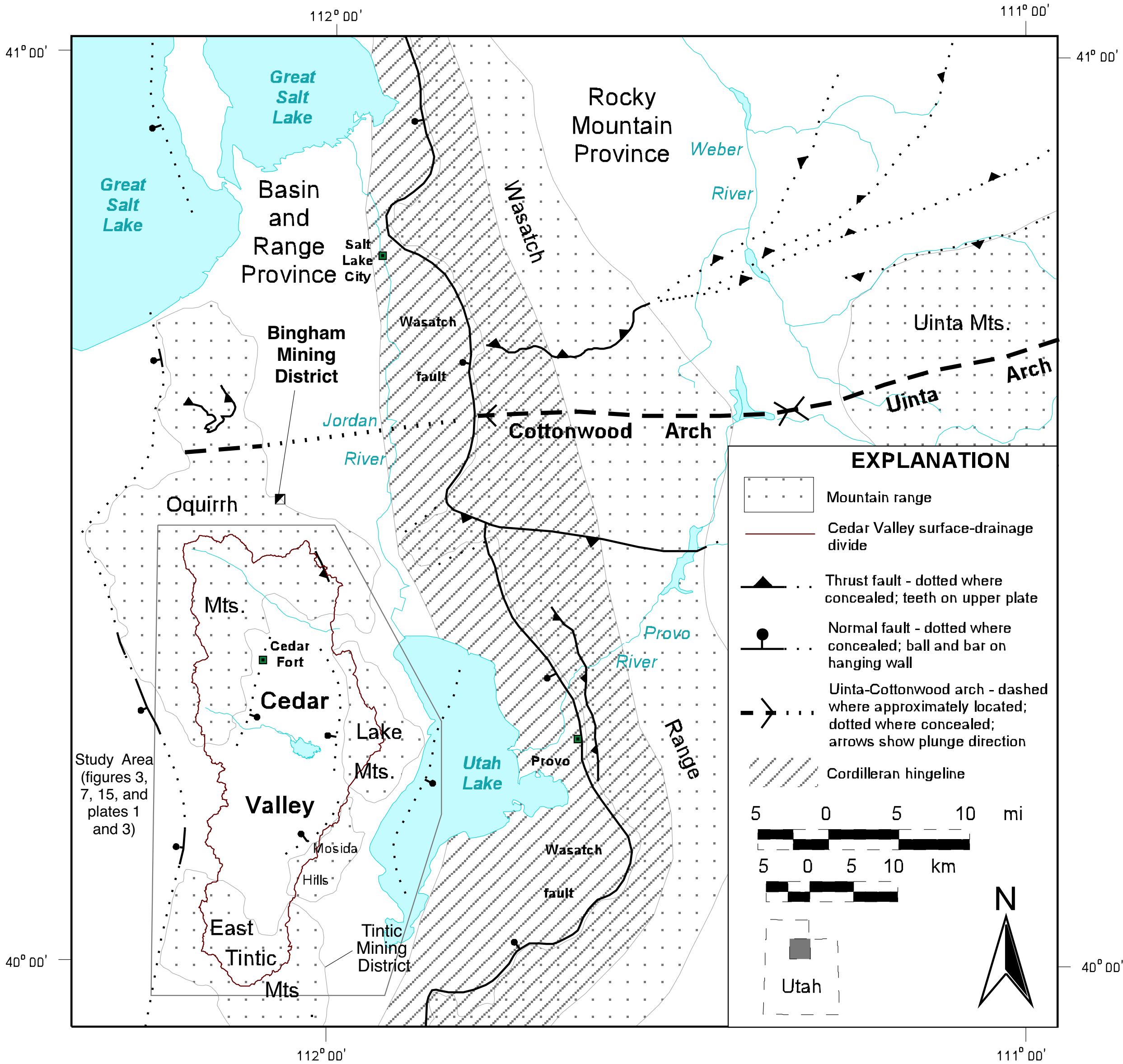

Figure 2. *Major tectonic and hydrologic features of north-central Utah.*

Because geology strongly influences the flow, storage, and occurrence of ground water, establishing the geologic framework of Cedar Valley is an essential component of understanding its present ground-water regime and anticipating the impact of future increases in withdrawal. This study outlines the geologic features of Cedar Valley that most directly influence ground water, including the stratigraphy and geometry of Quaternary-Tertiary basin-fill deposits, the stratigraphy and structure of bedrock units, and the geometry and hydrologic role of faults. The geologic data presented herein combines evaluation of previous work and conclusions based on my examination in the field of the geology of Cedar Valley and surrounding areas. Hydrologic data presented in this report are from previous studies, except for chemical analyses of new ground-water samples from wells in the northern part of Cedar Valley. The most recent comprehensive study of the hydrogeology of Cedar Valley is by Feltis (1967). The U.S. Geological Survey regularly measures ground-water levels in 27 wells in northern Cedar Valley (Burden and others, 2003, p. 103-105; U.S. Geological Survey, 2003), and Montgomery (1997) and Mower (1997) produced site-specific hydrogeologic reports. Part of the motivation for this study was to provide the geologic framework for a new, comprehensive study of the hydrogeology of Cedar Valley, including construction of a ground-water flow model, by the U.S. Geological Survey.

The main conclusions of this report are as follows.

(1) Quaternary-Tertiary alluvial basin fill forms the principal aquifer for Cedar Valley. These deposits form a roughly symmetrical ellipsoidal trough, up to 2,000 feet (600 m) thick; the area of maximum thickness lies below the geographic center of the northern half of the valley. Normal faults define the western and eastern basin margins and strongly influenced the thickness and facies distribution of sedimentary deposits in the basin. Below the Qua-

ternary and earliest Tertiary part of the basin fill lie partially cemented alluvial and lacustrine deposits of the late Tertiary Salt Lake Formation and middle Tertiary volcanic rocks.

(2) Basin-fill sediments grade from dominantly coarse-grained alluvial-fan deposits along the valley margins to interbedded lacustrine clay and minor sand in the basin center. This facies distribution has several important hydrogeologic consequences: (a) ground water is confined below lakebed deposits; (b) ground-water connection between basin-fill sediments and underlying bedrock is likely poor in the basin center, which contains intervening low-permeability deposits, and good along the basin margins where alluvial fans directly overlie bedrock; and (c) ground water in the transition zone between alluvial-fan and lakebed deposits is close to the surface and shows strong hydraulic communication parallel to the transition boundary.

(3) Bedrock aquifers below and adjacent to Cedar Valley include fractured Paleozoic limestone and interbedded limestone and quartzite. The best prospective aquifers include the Pennsylvanian Oquirrh Group, the upper and lower parts of the Mississippian Great Blue Formation, and the Mississippian Humbug Formation. The Mississippian-Pennsylvanian Manning Canyon Shale and the middle member of the Great Blue Limestone form aquitards.

(4) Structures in bedrock accommodate ground-water flow from Cedar Valley to Goshen Bay and northwestern Utah Lake, as discussed by Feltis (1967) and Dustin and Merritt (1980). Anticlines and faults are the most likely ground-water flow pathways. These structures strike NNW to WNW, oblique to the regional hydraulic gradient, in the northern Lake Mountains-Cedar Pass and Mosida Hills areas.

GEOLOGIC SETTING

Cedar Valley is oval in shape, having a north-south-trending long axis, flat valley floor, and gently sloping margins (figure 3). Cedar Valley is bounded on the east by the Lake Mountains and Mosida Hills (figures 3 and 4), on the west by the Thorpe Hills and Topliff Hill, and on the northwest by the southern Oquirrh Mountains (figures 3 and 5). The east-trending Traverse Mountains bound Cedar Valley on the north, and the East Tintic Mountains form the southern valley margin.

Geologic units in the study area include Middle Proterozoic through Permian sedimentary rocks; Tertiary volcanic, intrusive, and sedimentary rocks; and Quaternary clastic and lacustrine deposits (figures 6, 7, and 8; plate 1). Middle Proterozoic through Pennsylvanian rocks formed in the Cordilleran miogeocline (Armstrong, 1968), a slowly subsiding marine basin whose eastern margin was along the Cordilleran hingeline east of the study area (figure 2) (Picha and Gibson, 1985). Deposits of the Cordilleran miogeocline include Late Proterozoic to Cambrian quartzite and Cambrian to Permian carbonate and quartzite. Hydrologically important units in the study area include (figure 8): (1) the Mississippian Humbug Formation, composed of interbedded quartzite and limestone; (2) thick, shale-dominated sequences of the middle member of the Mississippian Great Blue Limestone and the Pennsylvanian-Mississippian Manning Canyon Shale; and (3) the Pennsylvanian Butterfield Peaks Formation, composed of interbedded limestone and quartzite (figure 9). The Butterfield Peaks Formation and the underlying West Canyon Limestone were deposited in the Late Paleozoic Oquirrh basin, a rapidly subsiding depression in northern Utah and southern Idaho (Armstrong, 1968). Mesozoic rocks are absent from the study area due to non-deposition and erosion, caused by uplift during Cretaceous to early Tertiary thrust faulting and folding.

Late Eocene to Oligocene volcanic and intrusive rocks formed in eruptive centers in the present-day Bingham mining district (Babcock and others, 1997; Deino and Keith, 1997; Waite and others, 1997) north of the study area and in the Tintic mining district (Morris and Lovering, 1979) south of the study area (figure 2). Volcanic deposits from these eruptive centers crop out in the northern and southern parts of the study area and in the Mosida Hills (figure 7 and plate 1) and may underlie Quaternary-Tertiary basin-fill deposits below Cedar Valley. These volcanic rocks are mostly potassium-rich andesite to rhyolite (Morris and Lovering, 1979; Waite and others, 1997).

Alluvial, lacustrine, and minor volcanic rocks of the Miocene-Pliocene Salt Lake Formation overlie the Tertiary volcanic rocks. The most extensive exposures of the Salt Lake Formation in the study area are in the northern Mosida Hills and southwestern Lake Mountains (figure 7; plate 1). The Salt Lake Formation likely underlies eastern Cedar Valley.

Freshwater lakes intermittently occupied Basin and Range valley floors during Quaternary time, and alluvial fans formed along the mountain fronts (Morrison, 1991; Oviatt and others, 1992). Quaternary basin-fill deposits in valleys of north-central Utah, therefore, include interlayered alluvial and lacustrine deposits. The position of the lake shorelines, and therefore the alluvial fan-lakebed sediment interface, varied over time (Morrison, 1991; Oviatt and others, 1992). The record of lake-level fluctuations and deposits prior to about 30 ka (thousand years) is sparse.

Lake Bonneville, the last major Quaternary lake, occupied much of Utah from about 30 to 10 ka and left an extensive record of deposition, erosion, and climatic fluctuations (Gilbert, 1890; Hunt and others, 1953; Oviatt and others, 1992). Lake Bonneville reached its greatest volume and highest shoreline elevation during the Bonneville stage from about 15 to 14.5 ka (Oviatt and others, 1992). Erosional shorelines and near-shore gravel bars in Cedar Valley are found at about 5,160 feet (1,570 m) (Biek, 2002b). Comparison of the valley-floor elevation of Cedar Valley (about 5,400 to 4,830 feet [1,645-1,470 m]) to the record of shoreline elevations of Lake Bonneville (Oviatt and others, 1992) suggests that Cedar Valley was submerged only during the late part of the transgression preceding the Bonneville stage and during the highstand. A playa may have occupied the Cedar Valley floor during the Provo stage - about 14.5 to 14 ka (shoreline elevation about 4,800 to 4,750 feet [1,460-

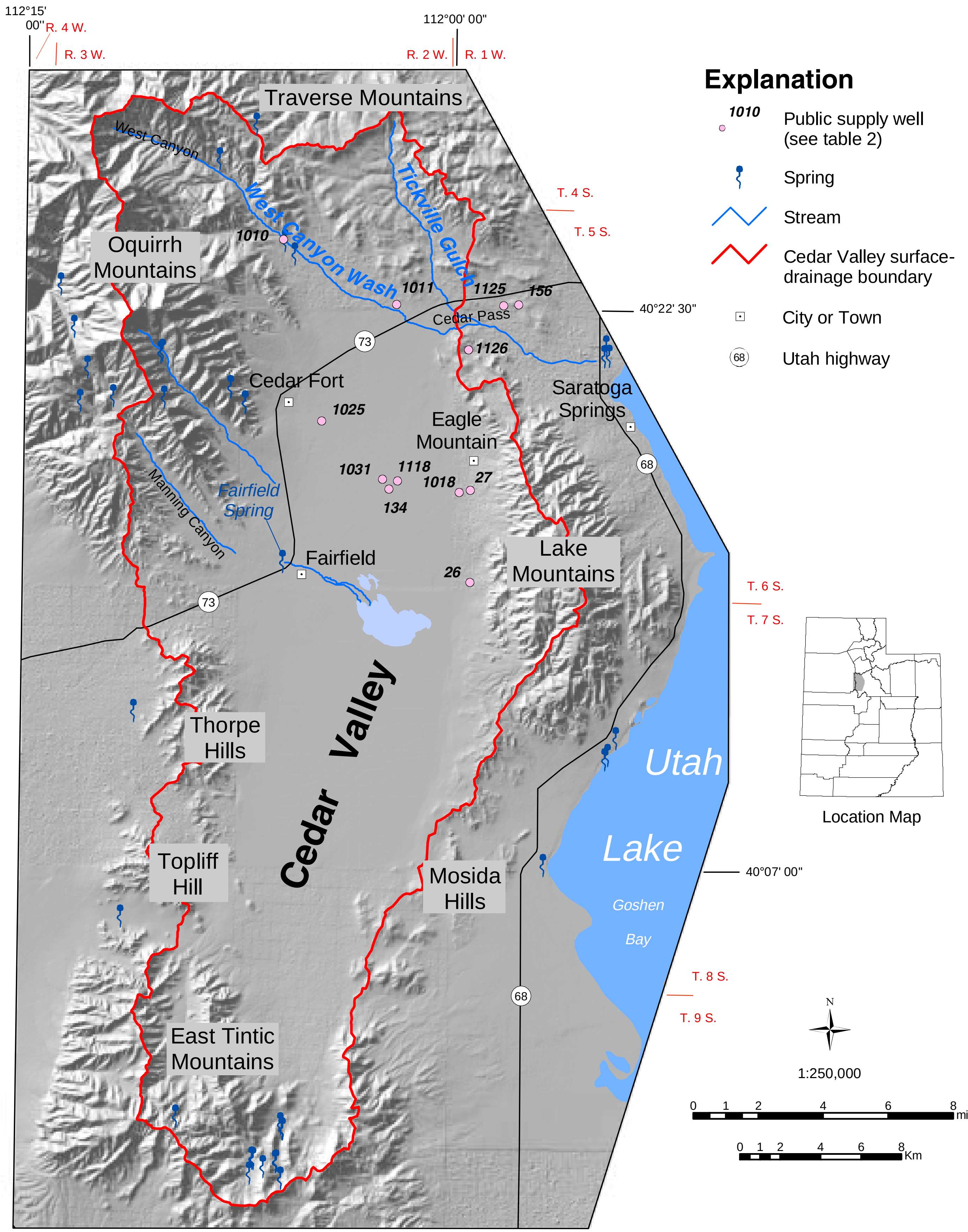

Figure 3. *Geographic features of the Cedar Valley study area.*

Figure 4. *View southwest of the Lake Mountains and northern Cedar Valley. The gently tapered shape of the range crest reflects the displacement profile on the Lake Mountains fault: displacement on the fault is greatest in the center, adjacent to the highest part of the footwall block, and decreases gradually toward either end. The Lake Mountains fault may be a barrier to ground-water flow from the range block to the basin fill.*

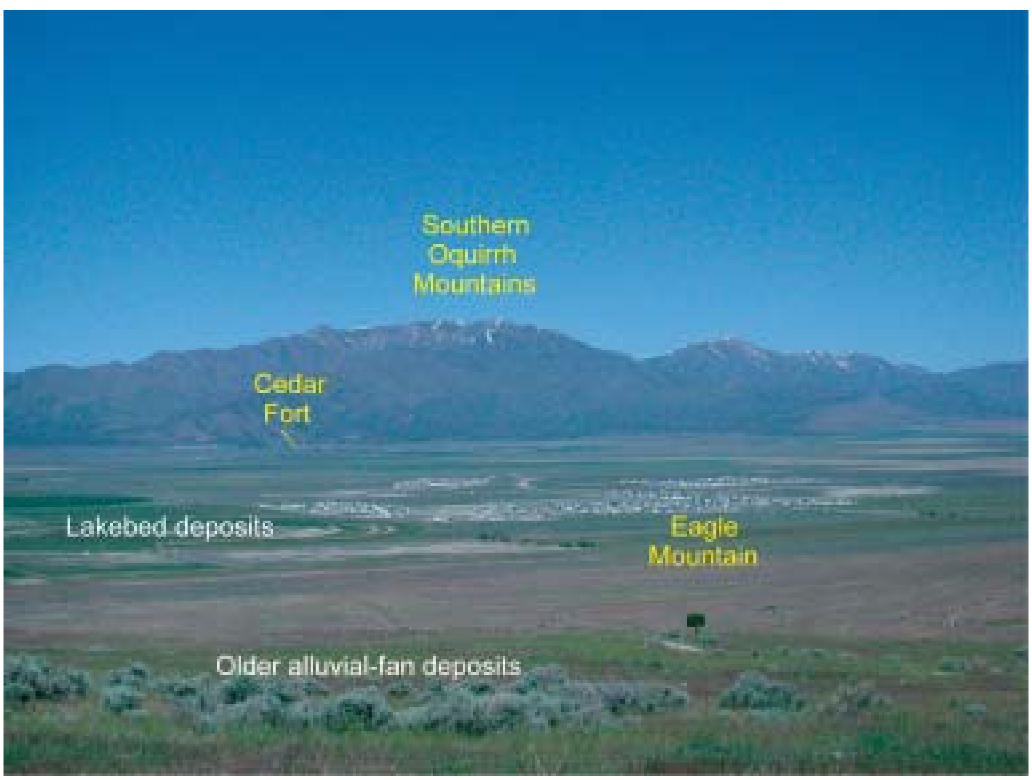

Figure 5. *View northwest of north-central Cedar Valley and the southern Oquirrh Mountains. The town of Eagle Mountain is in the foreground and Cedar Fort is in the background.*

Era	Period		Epoch	Age	Age estimates in Ma[1]
Cenozoic	Quaternary		Holocene		0.01
			Pleistocene		1.6
	Tertiary	Neogene	Pliocene		5.3
			Miocene		23.7
		Paleogene	Oligocene		36.6
			Eocene		57.8
			Paleocene		66.4
Mesozoic	Cretaceous		Late	Maastrichtian	74.5 (4)
				Campanian	84.0 (4.5)
				Santonian	87.5 (4.5)
				Coniacian	88.5 (2.5)
				Turonian	91.0 (2.5)
				Cenomanian	97.5 (2.5)
			Early	Aptian	113 (4)
				Albian	119 (9)
				Neocomian	144 (5)
	Jurassic		Late		163 (15)
			Middle		187 (34)
			Early		208 (18)
	Triassic		Late		230 (22)
			Middle		240 (22)
			Early		245 (20)

1. Age estimates are from Palmer (1983); uncertainties shown in parentheses except where none are reported.

Era	Period	Epoch	Age	Age estimates in Ma[1]
				245 (20)
Paleozoic	Permian	Late		258
		Early		286 (12)
	Pennsylvanian	Late		296 (10)
		Middle		315 (20)
		Early		320
	Mississippian	Late		352 (8)
		Early		360 (10)
	Devonian	Late		374 (18)
		Middle		387 (28)
		Early		408 (12)
	Silurian	Late		421 (12)
		Early		438 (12)
	Ordovician	Late		458 (16)
		Middle		478 (16)
		Early		505 (32)
	Cambrian	Late		523 (36)
		Middle		540 (28)
		Early		570
Proterozoic	Late Proterozoic			900
	Middle Proterozoic			1600
	Early Proterozoic			2500
Archean	Late Archean			3000
	Middle Archean			3400
	Early Archean			3800?

Figure 6. *Geologic time scale (after Palmer, 1983, and Hansen, 1991).*

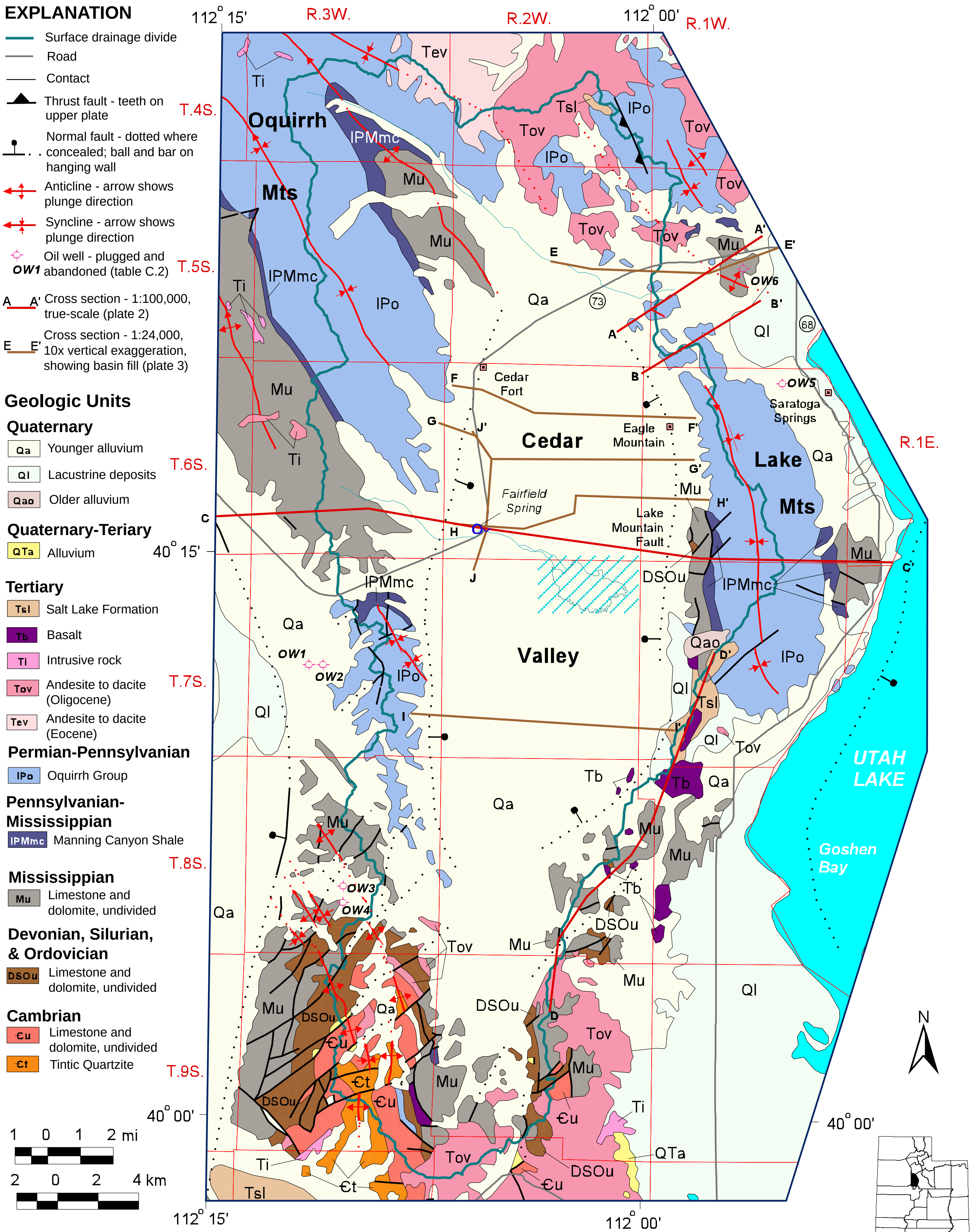

Figure 7. Simplified geologic map of the Cedar Valley study area (after Hintze and others, 2000).

Era	Period/ Epoch	Unit	Map Symbol (Plate 1, Figure 7)	Thickness in feet (m)	Lithology	Hydro-stratigraphy
CENOZOIC	Quaternary	Surficial and lacustrine deposits and basin fill	Q	0 - 2,000? (0 - 600?)		Unconsolidated aquifer
	Pliocene	Basalt	Tb	0 - 30 (0 - 10)		
	? Miocene ?	Salt Lake Formation	Tsl	0 - 400+ (0 - 120+)		Salt Lake Formation aquitard
	Oligocene	Oligocene intrusive rocks	Tio	–		Tertiary heterogeneous igneous-rock aquifer
		Oligocene volcanic rocks	Tvo	0 - 5,200 (0 - 1,580+)		
	? Eocene	Eocene intrusive rocks	Tie	–		
		Eocene volcanic rocks	Tve	0 - 1,400 (0 - 425)		
		Conglomerate	Tc	0 - 500+ (0 - 150+)		
PALEOZOIC	Pennsylvanian	Oquirrh Group, IPo: Bingham Mine Formation: Markham Member	IPbmm	3,700 (1,130)		Oquirrh Group carbonate-quartzite aquifer
		Bingham Mine Formation: Clipper Member	IPbmc	8,200 (2,500)		
		Butterfield Peaks Formation: upper unit	IPbpu	770 (235)		
		Butterfield Peaks Formation: lower unit	IPbpl	4,500 (1,307)		
		West Canyon Limestone	IPMwc	1,860 (570)		
	Mississippian	Manning Canyon Shale	IPMmc	1,200 - 1,560 (365 - 475)		Manning Canyon aquitard
		Great Blue Limestone Mgb: upper member	Mgbu	2,100 (640)		upper Great Blue aquifer
		Great Blue Limestone Mgb: middle member	Mgbm	850 (260)		Long Trail aquitard
		Great Blue Limestone Mgb: lower member	Mgbl	1,080 (330)		lower Great Blue aquifer
		Humbug Formation	Mh	650 - 1,035 (200 - 315)		lower Great Blue aquitard
		Deseret Limestone	Md	700 - 945 (215 - 290)		middle Paleozoic carbonate aquifer
		Gardison Limestone	Mg	450 - 680 (135 - 205)		

Era	Period	Unit	Map Symbol (Plate 1, Figure 7)	Thickness in feet (m)	Lithology	Hydro-stratigraphy
PALEOZOIC	Mississippian	Fitchville Formation	Mf	275 - 535 (85 - 165)		middle Paleozoic carbonate aquifer
	Devonian	Pinyon Peak Limestone and Victoria Formation	MDpv	450 (135)		
	Silurian / Ordovician	Devonian - Ordovician limestone and dolomite, undivided	DSOu	1,700 (520)		Opohonga aquitard
	Cambrian	Cambrian Limestone and dolomite, undivided	€u	2,750 (840)		lower Paleozoic carbonate aquifer
		Ophir Formation	€o	430 (130)		Ophir aquitard
		Tintic Quartzite	€t	2,350 - 3,200 (700 - 975)		Cambrian-Proterozoic quartzite aquifer
PTZ	Middle Proterozoic	Big Cottonwood Formation	Yb	1,675+ (510+)		

Explanation

Lithology

- fine sandstone
- coarse sandstone
- limestone
- limestone-bedded
- limestone-shaley
- conglomerate
- lava flows-basic
- lava flows-silicic
- breccia/tuff
- quartzite
- dolomite
- intrusive rock-silicic
- claystone
- cherty limestone

Figure 8. *Stratigraphic column for the Cedar Valley study area. Sources are listed in the description of map units (appendix A).*

Figure 9. *View north of part of the lower member of the Butterfield Peaks Formation in the west-central Lake Mountains, showing interlayered limestone (gray) and quartzite (tan) dipping about 40 degress east in the western limb of the Lake Mountains syncline.*

1,448 m]) (Oviatt and others, 1992), but there is no direct evidence of this.

Cedar Valley is a north-trending, fault-controlled basin in the eastern Basin and Range Province (figures 2, 3, and 7). The characteristic structure and topography of the Basin and Range Province formed during late Tertiary to Quaternary time by predominantly north-striking normal faulting and concurrent volcanism, which created north-trending, fault-bounded mountain ranges and adjacent basins (Stewart, 1998). Cedar Valley is about 20 miles (32 km) west of the Wasatch fault (figure 2), a large-displacement normal fault forming the eastern structural boundary of the Basin and Range Province (Zoback, 1983; Smith and Bruhn, 1984). Normal faults along the eastern and western margins of Cedar Valley are in the hanging wall of the Wasatch fault (figure 2). The Lake Mountains fault is the structural boundary between the Lake Mountains and Cedar Valley.

West- to southwest-directed thrust faults and related north- to northeast-striking folds deformed pre-Tertiary strata in the study area during Late Jurassic to earliest Tertiary time, when the Cordilleran thrust belt impinged on the region during the Sevier orogeny (Bryant and Nichols, 1988; Allmendinger, 1992; Royse, 1993; Willis, 1999). Folds and thrust faults exposed in the mountains and hills adjacent to Cedar Valley (figure 7; plate 1; cross sections A-A′ through D-D′, plate 2) formed at this time. The thrust faults transported rocks in their hanging walls eastward from their original locations (Royse, 1993). North- and south-directed reverse faults and east-striking folds also formed along the margins of the east-west trending Uinta-Cottonwood arch (figure 2) during latest Cretaceous to early Tertiary time (Bryant and Nichols, 1988; Allmendinger, 1992).

The events described above were superimposed on two older, large-scale crustal boundaries – the Uinta-Cottonwood arch and the Cordilleran hingeline (figure 2). The Uinta-Cottonwood arch lies along a major boundary between Archean and Proterozoic continental crust, and has strongly influenced the stratigraphic and structural evolution of the region (Bryant and Nichols, 1988). The Cordilleran hingeline is defined by a north-trending Late Proterozoic rift margin, and marks the line of dramatic westward thickening of Paleozoic sedimentary deposits of the Cordilleran miogeocline (Armstrong, 1968; Picha and Gibson, 1985).

HYDROLOGIC SETTING

Precipitation, Recharge, and Surface Water

Recharge to the bedrock aquifers of Cedar Valley occurs by infiltration of snowmelt and precipitation on areas of the surrounding mountains that receive more than 12 inches (31 cm) of precipitation annually (figure 10) (Feltis, 1967). Average annual precipitation increases with elevation, ranging from less than 12 inches per year (30 cm/yr) on the valley floor to over 40 inches per year (100 cm/yr) in the highest part of the southern Oquirrh Mountains (figure 10) (Ashcroft and others, 1992). Precipitation occurs chiefly during the winter as snowfall and during the late summer as thunderstorms. The average annual precipitation at Fairfield Spring was 11.8 inches per year (30 cm/yr) from 1943 to 2002 (Burden and others, 2003, p. 105).

Feltis (1967) estimated that 24,000 acre-feet (30 hm^3) of water is available for recharge to Cedar Valley annually, 85 percent of which falls as precipitation on bedrock above 5,000 feet (1,525 m) elevation in the southern Oquirrh

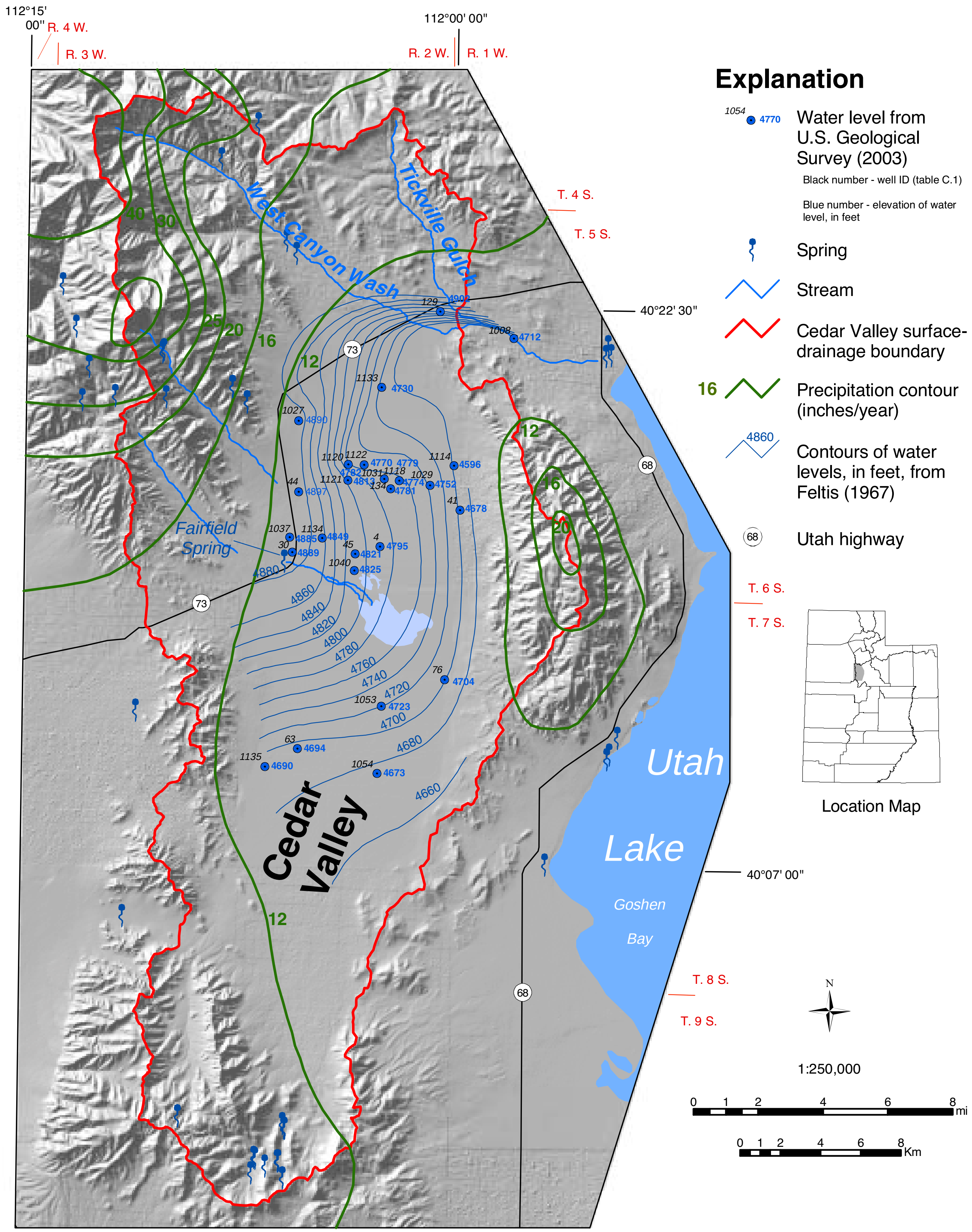

Figure 10. Hydrologic features of the Cedar Valley study area.

Mountains (figure 3). Ground water flows within bedrock from high to low elevations, and an unknown proportion of this water enters the basin-fill aquifer in the subsurface along the valley margins. Recharge to the basin-fill aquifer may also occur by infiltration of transient stream flow on the upper parts of the alluvial fans at the mouths of West Canyon, Pole Canyon, and Manning Canyon; Stone and others (2001) documented this type of recharge in a similar hydrologic and geologic setting in Nevada. West Canyon wash is the only perennial stream in the Cedar Valley hydrologic basin and contributes an estimated 1,000 acre-feet (1.2 hm^3) per year of recharge to the basin-fill aquifer, about 5 percent of the total stream flow (Feltis, 1967).

Ground Water

Water Levels and Movement

Water levels in the Cedar Valley basin-fill aquifer are highest adjacent to the southern Oquirrh Mountains and decrease gently to the east and southeast (figure 10). Water levels in the Cedar Pass area of the northeastern part of Cedar Valley are likely complexly distributed, but the overall hydraulic gradient is to the east to southeast, toward northern Utah Lake and the Jordan River (Mower, 1997).

Ground-water levels in three wells in the valley center, all screened in the basin-fill aquifer, rose 18 to 30 feet (6-9 m) between the mid-1960s and 2003 (Burden and others, 2003, p. 104). The water level in a well just west of Fairfield rose about 2 feet (0.6 m). Burden and others (2003) attributed these water-level rises to greater-than-average precipitation or recharge from surface water during the observation period.

The hydraulic gradient in the basin-fill aquifer in eastern Cedar Valley slopes toward the Lake Mountains, even within one-half mile (0.8 km) of the range front (figure 10), indicating that the Cedar Valley basin fill receives insignificant recharge from the Lake Mountains. Feltis (1967, p. 13) suggested that ground-water flow in bedrock in the Lake Mountains is structurally controlled and is to the east.

Discharge

General: Evapotranspiration, springs, wells, and subsurface outflow are sources of ground-water discharge from both basin-fill and bedrock aquifers in Cedar Valley (Feltis, 1967). Evapotranspiration occurs principally from irrigated cropland and from phreatophytes along surface drainages (Feltis, 1967). Based on values reported in Feltis (1967), Utah Division of Water Resources (2001), and Burden and others (2003), total annual discharge from the Cedar Valley ground-water system, including both bedrock and basin-fill aquifers, is about 7,000 acre-feet (9 hm^3) by evapotranspiration, roughly 650 acre-feet (0.8 hm^3) by domestic/public use, and 10,000 (Feltis, 1967) to 18,000 (Dustin and Merritt, 1980) acre-feet (12-22 hm^3) by subsurface outflow to the Utah Lake basin.

Springs: Table 1 summarizes the major springs in the Cedar Valley drainage basin that are used for irrigation and culinary purposes. Fairfield Spring typically discharged from 3 to 5 cubic feet per second (0.08-0.14 m^3/s), about 30 to 60 acre-feet per year, prior to 1966 (Feltis, 1967). The Fairfield Irrigation Company estimates that annual discharge from Fairfield Spring ranged from about 7 to 20 acre-feet (0.01-0.02 hm^3) between 1987 and 2002; about 7 to 13 acre-feet (0.01-0.02 hm^3) per year of this discharge is diverted for domestic use (Utah Division of Water Rights, 2003), and the remainder, if any, flows east to the valley center (figure 10). Fairfield Spring issues from the toe of the Manning Canyon alluvial fan, and its outflow crosses relatively impermeable clay-rich lakebed sediment. Most of the outflow, therefore, likely remains perched above fine-grained lakebed sediment, providing little or no recharge to the basin-fill aquifer.

Cedar Fort Culinary Water Company diverts 55 to 92 acre-feet per year (0.07-0.11 hm^3/yr) from two springs in the southern Oquirrh Mountains for domestic use (Utah Division of Water Rights, 2003). These springs issue from the bedding planes of fractured limestone and quartzite of the lower unit of the Pennsylvanian Butterfield Peaks Formation (table 1; plate 1) (Feltis, 1967). The water likely represents snowmelt from the southern Oquirrh Mountains and is part of a relatively small-scale, short-term bedrock flow system.

Wells: About 138 wells draw water from the basin-fill and bedrock aquifers beneath Cedar Valley (Utah Division of Water Rights unpublished data, 2001). Feltis (1967) reported that in 1965 wells withdrew about 2,000 to 4,000 acre-feet (2.5-5.0 hm^3). Well-withdrawal rates ranged from about 130 to 1,115 gallons per minute (494-4,240 L/min) (Feltis, 1967). Eagle Mountain City reported system withdrawals of about 500 acre-feet (0.6 hm^3) for 2000, 1,060 acre-feet (1.3 hm^3) for 2001, and 1,805 acre-feet (2.2 hm^3) for 2002 (Utah Division of Water Rights, 2003). Ground-water withdrawal from wells throughout Cedar Valley was 5,200 acre-feet (6.4 hm^3) in 2002, an increase of 1,400 acre-feet (1.7 hm^3) over the previous year (Burden and others, 2003). Burden and others (2003) estimated that 3,300 acre-feet (4.1 hm^3) of the total withdrawal in 2002 was used for irrigation and 1,900 acre-feet (2.3 hm^3) was for public/domestic supply.

Most domestic wells in Cedar Valley are located in and near the towns of Fairfield and Cedar Fort in the northwestern part of the valley and in Eagle Mountain City in the northeastern part of the valley. Most domestic wells in the northwestern valley are open in the basin-fill aquifer, whereas wells in the northeastern valley are open in either the basin-fill aquifer or underlying bedrock aquifers. Eagle Mountain City has several large, public-supply wells screened in the basin-fill aquifer, and one production well and four test wells in bedrock (table 2) (Utah Division of Water Rights, 2003). Irrigation wells are scattered throughout the valley, and the vast majority are open in the basin-fill aquifer.

Subsurface Outflow: Cedar Valley is between the southern Oquirrh Mountains and Utah Lake which are, respectively, important recharge and discharge areas within the Utah Lake hydrologic basin (figures 2, 3, and 10). Based on this relationship and on the difference between water levels in Cedar Valley and Utah Lake, Hunt and others (1953) and Feltis (1967) suggested that ground water flows from Cedar Valley to Goshen Bay of Utah Lake. Dustin and Merritt (1980) presented evidence reinforcing this hypothesis of ground-water seepage to western Utah Lake, including observations of numerous seeps, analysis of thermal imagery, and variations in lake-water chemistry. Montgomery (1995), in a hydro-

Table 1. *Records of selected springs in Cedar Valley, Utah County (Feltis, 1967, table 3, p. 26).*

ID[1]	Location[2]	Name	Formation	Nature of openings	Temperature °C	Yield (gpm)
S1	(C-4-2)26cbc	Tickville Spring	Qay	Large seep area in stream channel	-	10
S2	(C-4-3)20dba	-	IPbpl	Joints and solution openings in limestone	45	15
S3	(C-4-3)26cbd	Cottonwood Spring	IPbpl	Joints and solution openings in limestone	51	15
S4	(C-4-3)26dda	-	IPbpl	Joints and solution openings in limestone	49	15
S5	(C-4-3)27bab	-	IPbpl	Joints and solution openings in limestone	48	17
S6	(C-5-1)17bdc	-	Qay	Seep area in stream channel	-	<1
S7	(C-5-3)4cdc	-	IPbpl	Joints and solution openings in limestone	44	10
S8	(C-5-3)4dcd	-	Qay	Seep area in canyon fill	42	5
S9	(C-5-3)36cba	North Spring	IPbpl	Joints and solution openings in limestone	46	300
S10	(C-6-2)6cad	South Spring	Qay	Alluvium overlying Oquirrh Group	50	>124
S11	(C-6-2)29ccc-1	Fairfield Spring	Qaf	Large seep and spring area at toe of alluvial fan	52	2,070
S12	(C-6-3)1aad	Tunnel Spring	IPbpl	Joints and solution openings in limestone	47	>88
S13	(C-6-3)15bad	-	IPbpl	Joints and solution openings in limestone	52	7
S14	(C-9-2)29b,32c	-	Qay	Seep area	-	-

Notes

- No record

1. Corresponds to labels on plate 1 and ID in table C.1.
2. Locations given in U.S. Geological Survey notation - see figure C.1 for explanation.

Table 2. *Records of public-supply wells in Cedar Valley, Utah County.*

ID[1]	Owner	Location[2]	Depth to Bedrock[3]	Producing Unit[4]
26	Eagle Mountain City	S 256 W 957 E4 6S 1W 31	44	Mgb?
27	Eagle Mountain City	N 1,356 W 1,006 SE 6S 1W 18	>235	Basin fill
134	Eagle Mountain City	N 1,319 E 1,689 SW 6S 2W 14	>1,250	Basin fill
156	Eagle Mountain City test well #3	N 250 E 200 SW 5S 1W 16	80	Mgbu, Mgbl
1011	Eagle Mountain City test well #1	N 100 E 1,420 SW 5S 2W 14	40	IPbpl
1010 [5]	Cedar Fort Irrigation Co.	S 700 W 1,000 NE 5S 2W 7	20	Mgbu
1018 [6]	Eagle Mountain City	N 1,012 W 200 S4 18 6S 1W	349	IPbpl, Basin fill
1023	Eagle Mountain City	S 264 W 957 E4 6S 1W 31	193	Mgb?
1031	Eagle Mountain City	N 2,640 E 30 SW 6S 2W 14	>1,007	Basin fill
1033	White Hills Water Co.	S 1,050 E 50 NW 17 6S 2W	462	Basin fill
1118	Eagle Mountain City	N 2,697 E 3,128 SW 6S 2W 14	>810	Basin fill
1125	Eagle Mountain City test well #2	N 25 E 3,100 SW 5S 1W 17	135	Mgbu
1126	Eagle Mountain City test well #4	S 1,900 W 2,600 NE 5S 1W 30	35	IPbpl

Notes

1. Corresponds to labels on figure 3 and plate 1, ID numbers referenced in text, and ID column in table C.1.
2. Locations given in Point of Diversion (POD) notation - see figure C.2 for explanation.
3. Estimated depth to bedrock based on well drillers' logs. Logs are available from the Utah Division of Water Rights' Web site (<http://www.waterrights.utah.gov>).
4. Author's interpretations.
5. Well not currently in production.
6. Well location is uncertain; Montgomery (1995) lists the POD as N 840 W 278 S4 18 6S 1W, but the log he provides for this well has the POD listed in this table. Another well exists with the POD listed by Montgomery (1995) - see ID #77, table C.1.

geologic evaluation of eastern Cedar Valley, concurred with Feltis' (1967) conclusions. Mower (1997) and Jarvis (Oregon State University, written communication, 2003) report that unpublished water-level and chemical data indicate that some ground water exiting Cedar Valley beneath Cedar Pass flows toward the Jordan River.

Feltis (1967) estimated that about 10,000 acre-feet (12 hm^3) of ground water per year exited the Cedar Valley hydrologic system by subsurface outflow through bedrock along the eastern basin boundary, and that of this total about 3,000 acre-feet (4 hm^3) passed under the Mosida Hills area and about 7,000 acre-feet (9 hm^3) passed below Cedar Pass and the northern Lake Mountains. Feltis (1967) based his estimates on calculations of ground-water flow using Darcy's Law and estimates of basin-fill transmissivity and hydraulic gradient. Brooks and Stolp (1995) estimated that about 5,200 acre-feet per year (6 hm^3) flows from the basin fill in eastern Goshen Valley into Utah Lake, using a similar technique. Not all, but presumably most, of this flow would originate in bedrock aquifers in Cedar Valley; the remainder would come from the Lake Mountains. Dustin and Merritt (1980) estimated that up to 18,000 acre-feet (22 hm^3) of ground water per year enters Utah Lake by subsurface outflow in bedrock below the Mosida Hills, based on computer simulations. Dustin and Merritt's (1980) estimate represents a significant proportion of Feltis' (1967) estimate of the total annual water available to Cedar Valley for recharge, about 24,000 acre-feet (30 hm^3). These disparate estimates cannot be reconciled without additional data on ground-water levels and precipitation between southeastern Cedar Valley and Goshen Bay.

The range of estimated subsurface outflow from Cedar Valley to Utah Lake represents about 10 to 18 percent of the total annual flow of ground water into Utah Lake (Dustin and Merritt, 1980), and 2 to 3 percent of the total inflow including both surface and ground-water sources (based on inflow estimates by the Utah Division of Water Resources, 1997, p. 5-3).

GROUND-WATER CHEMISTRY

Introduction

Feltis (1967) reported ground-water-chemistry data for 21 wells and 8 springs, and specific conductance data for one well and six springs in Cedar Valley (table B.1). These data revealed that ground-water quality in the basin-fill aquifer was good in all but the southeastern part of the valley, which had high salinity- and sodium-hazard indices and high total-dissolved-solids concentrations. Some ground water along the northeastern valley margin also had high total-dissolved-solids concentrations. Nitrate concentrations were less than 4 mg/L throughout the valley.

Feltis' (1967) ground-water-chemistry data show three geographic groups of ground-water quality and composition, in the northwestern, northeastern, and southeastern parts of the valley (figures 11 and 12; table B.2). Ground water in both basin-fill and bedrock aquifers in northwestern Cedar Valley is calcium-bicarbonate type and has low total dissolved solids (TDS) (average 311 mg/L for 18 basin-fill samples and 341 mg/L for seven bedrock samples). Ground water in bedrock aquifers in northeastern Cedar Valley has higher TDS (average 761 mg/L for seven samples), higher hardness, and is enriched in chloride, calcium, and sulfate compared to the northwestern group. Ground water in basin fill in the southeastern part of Cedar Valley has substantially higher TDS (average 1,823 mg/L for three samples), lower hardness, is enriched in sodium and sulfate, and is depleted in calcium compared to basin-fill samples from northwestern Cedar Valley. These evaluations of relative enrichment or depletion of chemical species between geographic areas are based on comparing the ratios of average elemental or molecular concentrations to average total-dissolved-solids concentrations (table B.2).

The Utah Department of Agriculture and Food (UDAF) collected and analyzed water-quality samples from 23 wells in Cedar Valley in October 2001 to confirm the trends shown by Feltis (1967) and to identify possible changes since the mid-1960s. Wells were selected for sampling to provide the best geographic coverage possible; unfortunately, only a limited number of wells in northern Cedar Valley could be accessed. The UDAF analyzed the ground water for general chemistry, nutrients, and bacteria (table B.3) (Quilter, 2001).

Results

Total Dissolved Solids

Total-dissolved-solids (TDS) concentrations for the 23 samples obtained in 2001 by the UDAF ranged from 375 to 1,898 mg/L (table B.3); concentrations generally increase from west to east, although the highest value is in the central part of northern Cedar Valley (figure 13; table B.3). Total-dissolved-solids concentrations in the Cedar Fort, Fairfield, and Cedar Pass areas are generally higher than those reported by Feltis (1967) (figures 11, 12, and 13). The chemical composition of the newer ground-water samples vary from west to east in a similar manner to Feltis' (1967) samples, showing increasing sodium plus potassium, chloride, and sulfur and decreasing calcium based on comparing the ratios of the averages of elemental or molecular concentrations to average TDS concentrations (table B.4; figure 13). Limited distribution of the UDAF samples prevented confirmation of the chemical trends from the northwestern to the southeastern parts of the valley shown by Feltis (1967).

Nitrate Concentrations

The U.S. ground-water quality standard (maximum concentration) for nitrate is 10 mg/L (U.S. Environmental Protection Agency, 2002). More than 10 mg/L of nitrate in drinking water can result in a condition known as methoglobinemia, or "blue baby syndrome" (Comley, 1945) in infants under six months and can be life threatening without immediate medical attention (U.S. Environmental Protection Agency, 2002). This condition is characterized by a reduced ability for blood to carry oxygen. Nitrate concentrations in Cedar Valley's basin-fill aquifer range from 0.0 to 10.0 mg/L (figure 14), and average 2.2 mg/L. Ground water from one privately owned well in Cedar Fort equaled the ground-water quality (health) standard of 10 mg/L for nitrate.

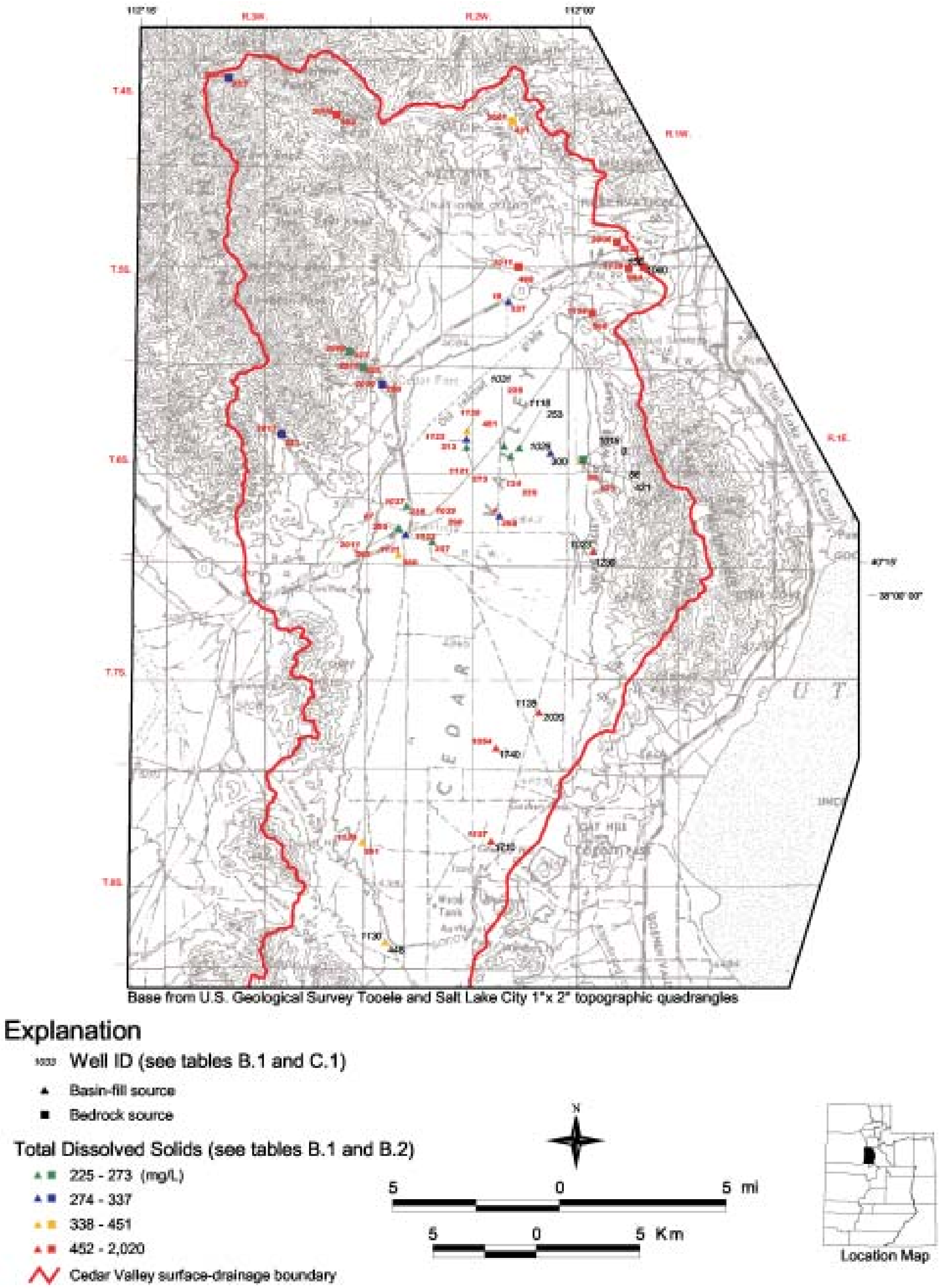

Figure 11. *Total-dissolved-solids concentrations of ground-water samples (Feltis, 1967; Montgomery Watson, 2000).*

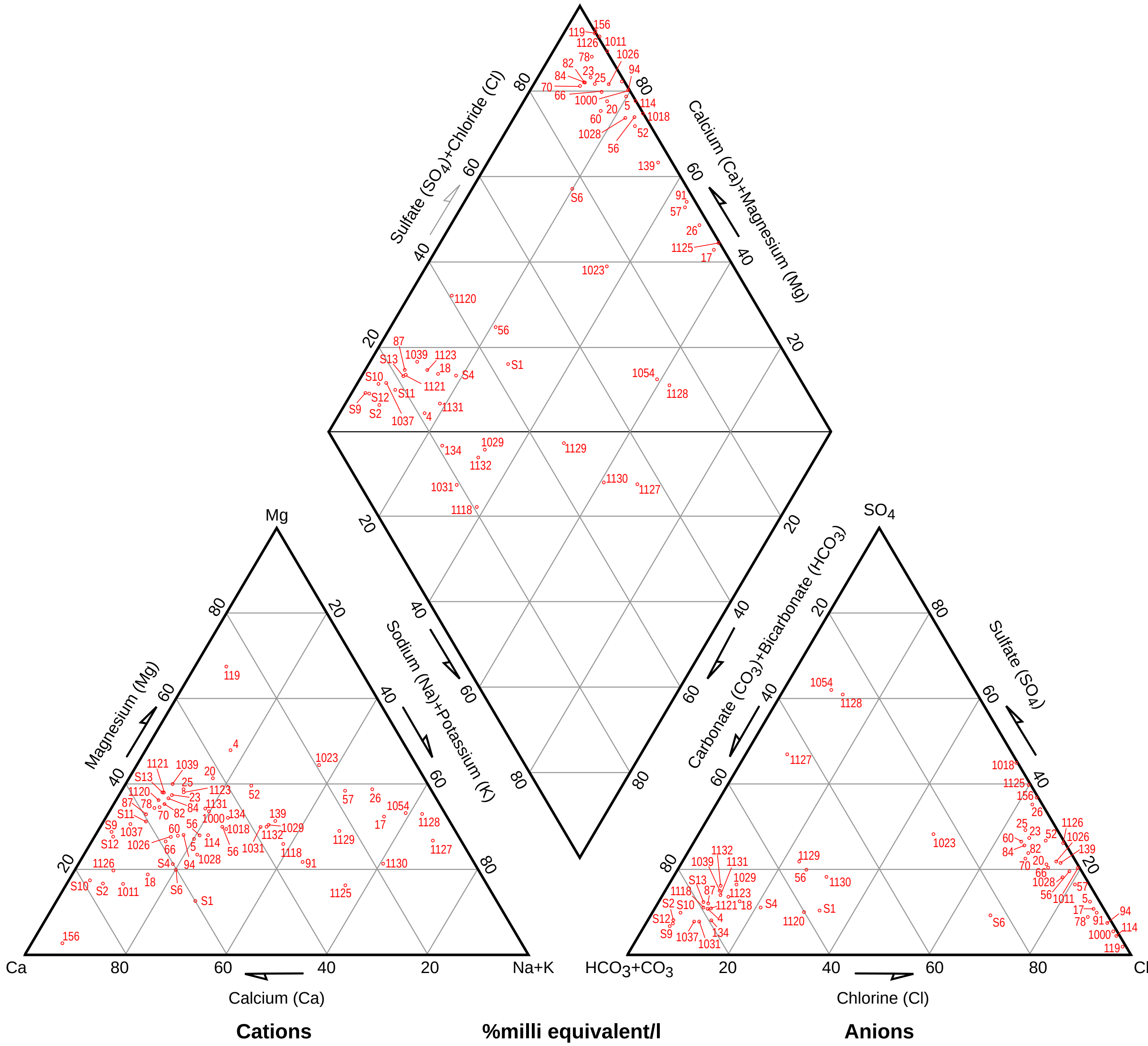

Figure 12. *Trilinear plots of Cedar Valley ground-water ion chemistry (data from Feltis, 1967 and this study).*

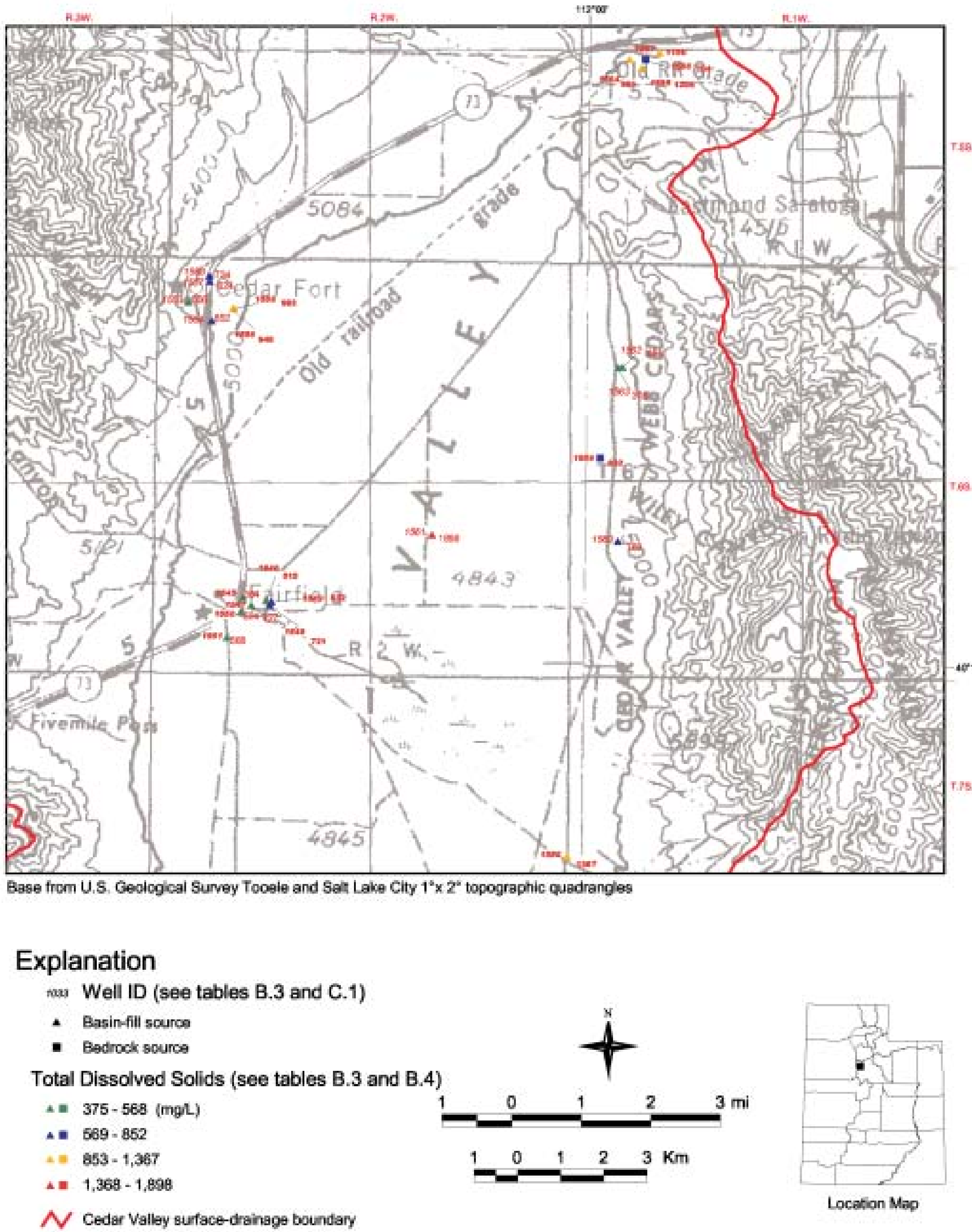

Figure 13. *Total-dissolved-solids concentrations of ground-water samples collected and analyzed by the Utah Department of Agriculture and Food.*

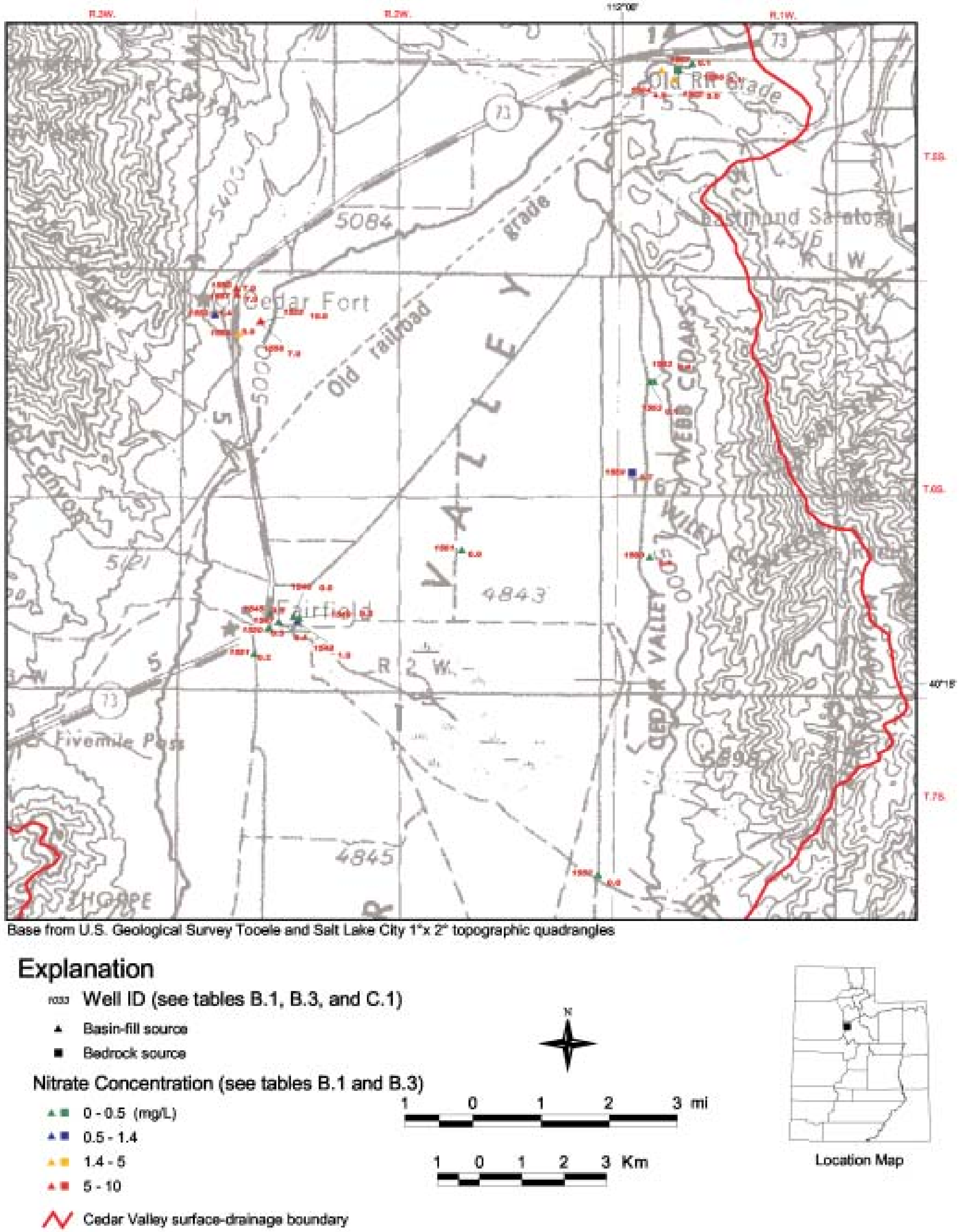

Figure 14. *Nitrate concentrations of ground-water samples collected and analyzed by the Utah Department of Agriculture and Food (reported as nitrate) and Eagle Mountain City (reported as nitrogen).*

Discussion

The increase in sodium and chloride concentrations from northwestern Cedar Valley to the Cedar Pass-western Lake Mountains area may result from mixing of ground water with water rising from greater depth along the Lake Mountains fault. Ground water migrating upward along the Lake Mountains fault would likely be enriched in sodium and chloride, based on comparison with samples from fault-controlled springs on Lincoln Point and Bird Island, along the southeastern margin of Utah Lake about 18 miles (29 km) southeast of Cedar Pass, analyzed by Baskin and others (1994). Mixing of a relatively small volume of sodium- and chloride-enriched water migrating along the Lake Mountains fault could result in the observed increases in sodium, chloride, and TDS concentrations in ground water along the eastern Cedar Valley margin. Montgomery (1995) suggested that a well for Eagle Mountain City along the west-central margin of the Lake Mountains (ID 1018, tables 2 and C.1) derives some of its production from sodium- and chloride-enriched warm water rising along the Lake Mountains fault, consistent with the interpretation presented here.

The increased TDS, sodium plus potassium, and sulfate and decreased calcium concentrations in ground water in southeastern Cedar Valley may result from interaction of ground water with Tertiary volcanic deposits or Tertiary and Quaternary clay-rich sediment. Oligocene-age volcanic breccia and tuff is exposed in the Mosida Hills and southern Lake Mountains, and is likely present in the subsurface along the southeastern valley margin. Chemical reactions with albite-rich plagioclase and ferrous sulfides in the volcanic rocks would increase the sodium, sulfate, and TDS concentrations of the ground water in southeastern Cedar Valley. Reactions with oligoclase would, however, be expected to increase the potassium content of the water; this trend is not observed. Oligocene quartz latitic volcanic deposits in the northern East Tintic Mountains contain albite-rich plagioclase, oligoclase, and about 0.2 to 0.5 percent sulfate (Morris and Lovering, 1979). Spring water issuing from Oligocene quartz latitic and andesitic lava and breccia in southwestern Colorado (Miller, 2002) has similar composition to the ground water in southwestern Cedar Valley. Alternatively, cation-exchange reactions with clay-rich Lake Bonneville or Salt Lake Formation sediments could increase the sodium concentration at the expense of calcium, whereas the sulfate would be derived from ferrous sulfides (Hem, 1985). Sulfide minerals may be present in clay deposits of the Salt Lake Formation, some of which may be hydrothermally altered volcanic tuff (Bullock, 1951).

GEOLOGY AND HYDROGEOLOGY OF BASIN-FILL DEPOSITS

Introduction

Quaternary-Tertiary basin fill is presently the principal aquifer for Cedar Valley. The basin fill is composed of coarse-grained alluvial-fan deposits along the valley margins, and fine-grained lakebed deposits interbedded with alluvial and distal alluvial-fan deposits in the valley center. The basin-fill deposits overlie semiconsolidated alluvial and volcanic deposits of the Miocene Salt Lake Formation or, where the Salt Lake Formation is absent, rocks of the Oquirrh Group or older bedrock units.

Depositional Environments

Cedar Valley formed as a topographic feature during Pliocene to Quaternary time due to normal faulting along the present eastern and western valley margins. Alluvial fans emanated from the uplifting mountains bounding Cedar Valley, interfingering with and grading into clay-rich lacustrine and playa(?) deposits in the valley center. The position of the alluvium-lakebed interface during Quaternary time varied with fluctuations in the lake shoreline; these fluctuations were driven by climate variations that produced a series of alternating glacial and interglacial events (Morrison, 1991; Oviatt and others, 1992). During times when no lake was present in Cedar Valley, distal alluvial-fan and alluvial sediments were likely deposited in the valley center.

The Salt Lake Formation, like the younger overlying deposits, formed in intergrading alluvial and lacustrine environments. The distribution and thickness of the Salt Lake Formation below Cedar Valley is poorly known due to a lack of subsurface data.

Composition and Lithology

Quaternary alluvial-fan deposits in Cedar Valley consist of unconsolidated, poorly sorted, structureless to well-bedded pebble to boulder gravel. Clasts are limestone, quartzite, and minor volcanic rocks derived from adjacent mountains. Lakebed deposits are well-layered clay, locally containing minor silt and/or sand. Shoreline deposits consist of well-sorted sand and gravel, and are of limited extent and thickness.

The Salt Lake Formation exposed along the margins of Cedar Valley consists primarily of clayey siltstone, interbedded with volumetrically minor sandstone, conglomerate, and limestone. The siltstone is well layered and contains varying amounts of volcanic detritus, silt, and sand. The limestone is white, fine grained, very hard, poorly layered, and is found in beds about 3 to 6 feet (1-2 m) thick. Sparsely exposed, interbedded or gradational sandstone and conglomerate are pale gray, semiconsolidated, and moderately well sorted. The Salt Lake Formation overlies semiconsolidated Oligocene volcanic rocks in the Mosida Hills and southern Lake Mountains.

Cross sections E-E′ through J-J′ (plate 3) illustrate the distribution of coarse- and fine-grained deposits below Cedar Valley. These sections are derived from water-well drillers' logs available from the Utah Division of Water Rights (well numbers on the cross sections are cross-referenced to the ID column in table C.1). The sampling interval and detail of descriptions vary, and compositional data are rarely provided. The drillers' interpretations of grain size and composition were taken at face value and not reinterpreted. Because of these uncertainties, correlations of sediment types between adjacent wells and across large parts of the sections are speculative. The cross sections are, therefore, schematic and generalized, as indicated by the choice of broadly inclusive grain-size units. The cross sections are vertically exaggerated 10 times to illustrate interpreted interbedding and lateral facies variations, so they do not represent the true geometry of the facies.

The coarse deposits shown on the cross sections are composed primarily of sand- to boulder-size clasts, contain variable amounts of silt and clay, and are interpreted as alluvial-fan and stream deposits. The fine-grained deposits are composed of clay to silt and lack gravel-size particles, and are interpreted as lakebed deposits, except where they are thin beds within gravel-dominated deposits, in which case they are interpreted as overbank deposits. Because the logs do not provide the relative proportions of different size particles, some deposits classified as coarse-grained may consist primarily of clay or silt with scattered gravel- or boulder-size clasts, and may represent mixed lakebed and alluvial-fan deposits.

Cross sections E-E′ through J-J′ (plate 3) illustrate the extent and nature of the unconsolidated basin-fill deposits below Cedar Valley and the locations of concealed normal faults along the valley margins, but should be viewed with the preceding cautionary notes in mind. Cross sections F-F′, G-G′, and H-H′ (plate 3) traverse the northern part of Cedar Valley perpendicular to the valley axis. These sections show that alluvial fans at depth prograde toward the basin center to varying distances, and the central part of the basin fill is composed almost entirely of clay-rich lakebed deposits. The thickness and lateral continuity of alluvial-fan and lakebed sediments vary both transverse and parallel to the valley axis. The distance the alluvial fans prograded toward the valley center was likely a complex function of lake level, climate, and subsidence of the basin margins in the hanging walls of the basin-bounding faults. Cross sections F-F′, G-G′, and H-H′ (plate 3) delineate range-bounding normal faults along the eastern and western basin margins, based on abrupt changes in depth to bedrock

Cross section J-J′ (plate 3) traverses the toe of the Manning Canyon alluvial fan parallel to the valley axis, and illustrates complex interlayering of alluvial-fan and lakebed sediments. Cross section I-I′ (plate 3) illustrates that the southern part of the basin has a distinctly lower proportion of alluvial-fan to lakebed sediment than the northern part of the basin. Cross section E-E′ (plate 3) illustrates complex structure and highly variable basin-fill thickness below the Cedar Pass area in the northeastern part of Cedar Valley.

Basin Structure and Evolution

The depositional basin below Cedar Valley formed in a graben, bounded on the east by a west-side-down normal fault and on the west by an east-side-down normal fault (cross section C-C′, plate 2). Displacement on these faults during late Tertiary to early Quaternary time caused the Cedar Valley basin to subside in the mutual hanging wall of the graben-bounding normal faults, while the uplifting footwalls formed mountain ranges that eroded and shed sediment into the basin.

The Bouguer gravity-anomaly map of Cedar Valley (figure 15) illustrates the general form of the Tertiary-Quaternary depositional basin; the more negative anomaly values represent thicker basin-fill sediment accumulations. The basin-fill deposits occupy a roughly symmetric, north-south-trending, oval-shaped basin beneath Cedar Valley. The area of maximum basin depth is directly west of the highest part of the Lake Mountains; both features reflect a displacement gradient along the eastern basin-bounding Lake Mountains fault, where displacement is greatest along the central part of the fault and gradually decreases to the north and south. The mountains bounding the southeastern and western valley margins have less relief than the central Lake Mountains, and the adjacent sections of the basin-bounding faults likely accommodated proportionately less displacement (figure 4), assuming relatively flat pre-faulting topography.

Plate 4 is a schematic isopach map showing the thickness of unconsolidated basin-fill deposits beneath Cedar Valley. This map was constructed from water-well drillers' logs available from the Utah Division of Water Rights (table C.1). The drillers' interpretations of depth to bedrock were accepted at face value, except in rare cases where nearby wells indicated greatly different depths to bedrock. In such cases, the value more consistent with data from other nearby wells and position within the valley was chosen. Relatively few wells in Cedar Valley encounter bedrock, so most logs end in unconsolidated deposits and provide only minimum values for basin depth. In the central part of Cedar Valley, contours are relatively poorly constrained and were drawn to conform to the shape of the Bouguer gravity-anomaly map.

The well drillers likely did not differentiate between the Salt Lake Formation and overlying late Tertiary-Quaternary unconsolidated deposits, so the basin-fill depths given on plate 4 likely include an unknown thickness of Salt Lake Formation and, possibly, Tertiary volcanic rocks. The thickness and distribution of the Salt Lake Formation and Tertiary volcanic rocks below Cedar Valley are not known. The Manning Canyon Shale potentially could have been interpreted by drillers as unconsolidated clay-rich deposits where it underlies basin-fill deposits. The values given on plate 4 should, therefore, be interpreted as maximum depths to bedrock.

Based on their composition and greater degree of cementation, the Salt Lake Formation and Tertiary volcanic rocks probably have substantially lower hydraulic conductivity than the overlying late Tertiary-Quaternary deposits. The thickness of basin-fill deposits given on plate 4 is, therefore, greater than the thickness of the highly transmissive Cedar Valley basin-fill aquifer.

Hydrologic Properties

Data characterizing the hydrologic properties of the Cedar Valley basin-fill aquifer are sparse. Based on results of aquifer tests and specific-capacity tests, Feltis (1967) suggested that transmissivity increases from the northern valley center toward the north and west. Feltis (1967) did not report specific-capacity test data, but presented the results of the drawdown (pumping) portion of an aquifer test performed during spring 1966 and of the recovery portion of an aquifer test performed during fall 1965. The 1966 aquifer test included water-level measurements for three observation wells, yielding transmissivity estimates of about 3,500, 1,600, and 1,100 feet squared per day (325, 149, and 102 m^2/day, respectively) (figure 16) (Feltis, 1967, p. 15). The 1965 aquifer test included data from two irrigation wells, yielding transmissivity estimates of about 1,200 and 700 feet

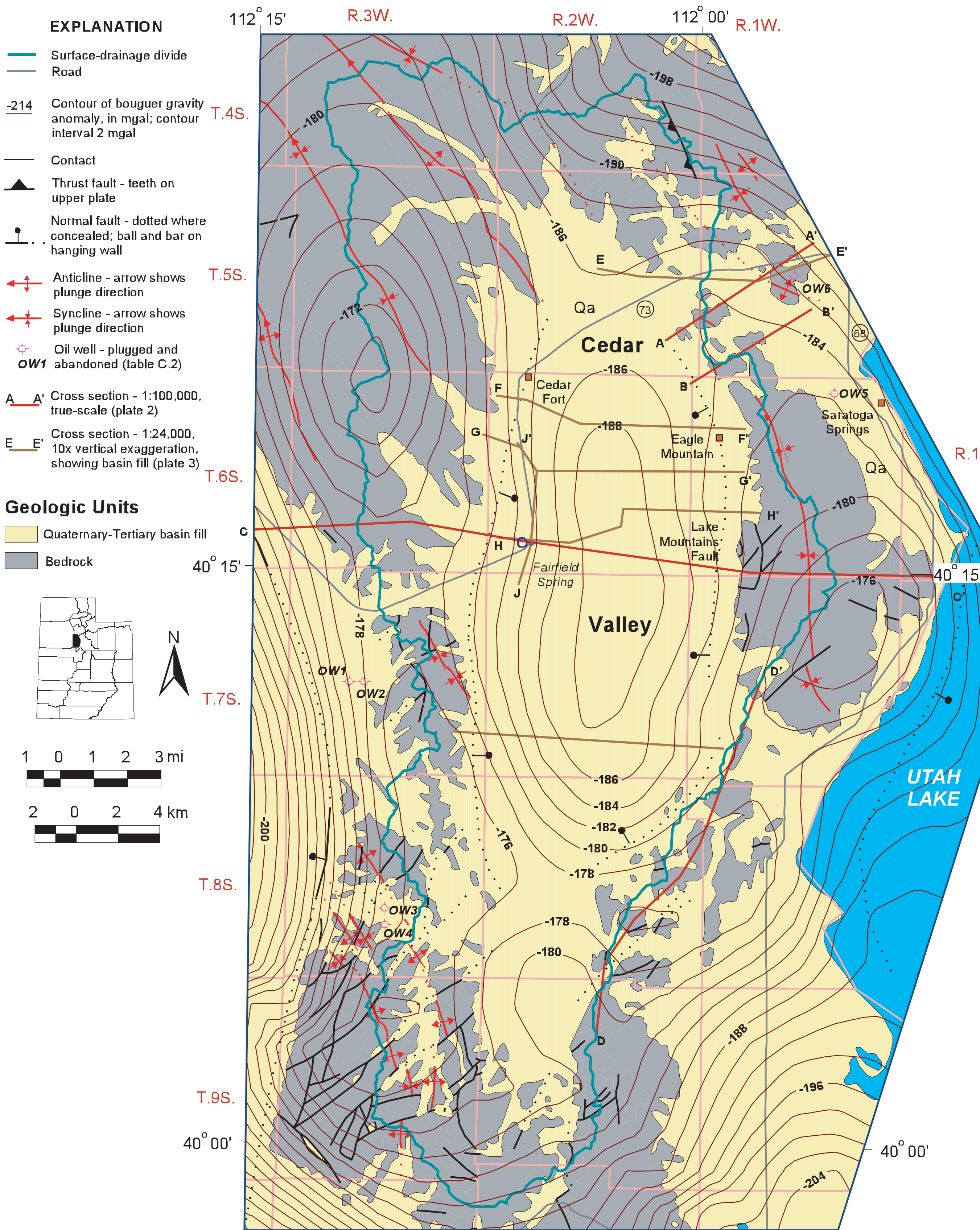

Figure 15. *Bouguer gravity map of Cedar Valley (data from Bankey and others, 1998).*

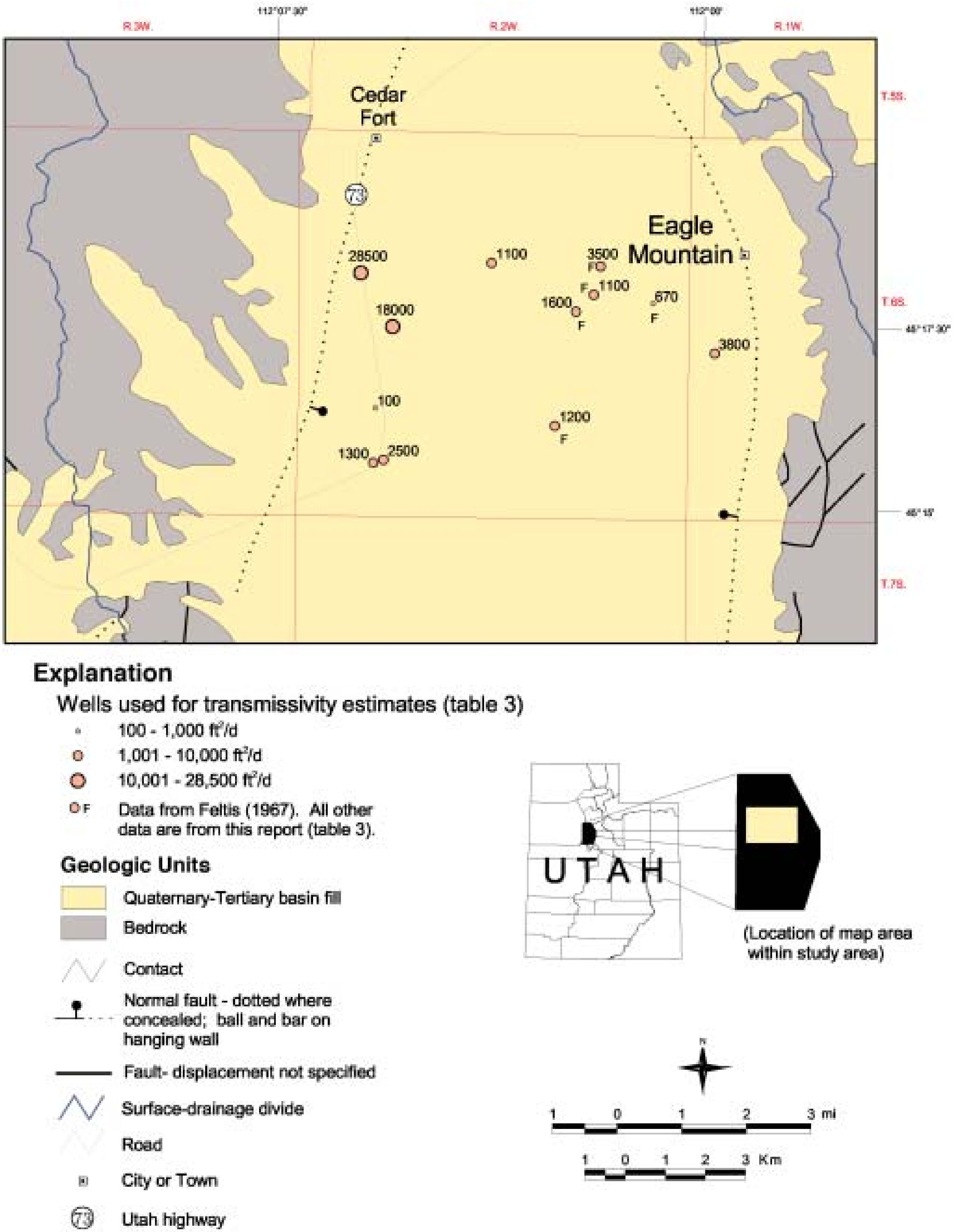

Figure 16. *Distribution of transmissivity estimates for the basin-fill aquifer, Cedar Valley (see table 3 and text).*

squared per day (112 and 65 m^2/day, respectively) (figure 16) (Feltis, 1967, p. 15).

To increase the number and improve spatial distribution of transmissivity estimates for the Cedar Valley basin fill, I calculated seven new transmissivity estimates using specific-capacity test data from drillers' logs of water wells screened in the basin-fill aquifer (table 3). I derived these transmissivity estimates using Bradbury and Rothschild's (1985) algorithm TGUESS, which is based on the equations of Theis (1963), and accounts for the effects of well-bore storage, partial aquifer penetration, and limited perforation intervals. For this analysis, only specific-capacity tests longer than 8 hours were included. Despite these precautions, the seven new transmissivity estimates should be regarded as less accurate than results from aquifer tests involving analysis of time-drawdown data, such as those reported by Feltis (1967). The new transmissivity estimates range from about 100 to 28,000 feet squared per day (9-2,600 m^2/day) (table 3; figure 16).

The expanded transmissivity estimates lack a strong spatial relationship to geologic or geographic features in Cedar Valley, except that the two highest estimates are in the northwestern part of the valley in the Pole Canyon alluvial fan. Based on facies distributions in basin-fill deposits (plate 1; cross sections F-F′ through J-J′, plate 3), transmissivity should increase toward the basin margins as the relative proportion of coarse-grained alluvial-fan deposits increases. The cross sections on plate 3 also show that the lateral extent of alluvial-fan deposits varies substantially with depth. The lack of a clear spatial correlation between sediment type and transmissivity may be due in part to the interception of lakebed sediments by some wells near the valley margins, or to varying correlation of perforation intervals with coarse-grained deposits.

Hydrologic Connection Between Basin Fill and Bedrock

Feltis (1967, p. 12) stated, "nearly all the ground water in the central and southern parts of the valley has infiltrated along the Pole Canyon syncline, and moved through fractures and solution channels in the rock, down the syncline, and into the valley fill." This statement clearly implies good hydrologic connection between bedrock and basin fill in the northwestern part of Cedar Valley. This section explores the hydrologic connection between basin fill and bedrock for the entire valley.

Hydrologic communication between bedrock and basin fill is likely greatest along the valley margins where alluvial-fan deposits directly overlie bedrock, and limited where lakebed deposits, the Salt Lake Formation, and/or Tertiary volcanic rocks overlie bedrock, or where shale and claystone of the Manning Canyon Shale and Great Blue Formation directly underlie alluvium such as in the Cedar Pass area and the northern valley margin. Alluvial-fan deposits may directly overlie bedrock in the southern Mosida Hills and along the entire western basin margin.

Based on exposures adjacent to the valley margins and on limited well-log data, the Salt Lake Formation overlies bedrock in the subsurface in the Cedar Pass area, in the southern Lake Mountains-northern Mosida Hills area, and in the southern part of the valley between the two prongs of the northern East Tintic Mountains. Detailed water-well logs by the U.S. Geological Survey (log of well [C-5-2]24aaa-1, reproduced in Feltis, 1967, table 7, p. 31; ID 1113, table C.1) and Wallace (2002; ID 136, table C.1) confirm the presence of volcanic deposits and the Salt Lake Formation in the subsurface below Cedar Pass. Volcanic rocks may also underlie the Salt Lake Formation in the subsurface along the western margin of the Lake Mountains. These deposits, when formed, would have been part of a continuous belt of volcanic rocks between the southern Traverse Mountains and southern Lake Mountains.

Volcanic rocks and/or Salt Lake Formation may also lie beneath much of the basin center, although well logs do not directly confirm their presence. In several logs of deep water wells in north-central Cedar Valley, clay-rich lakebed deposits are underlain by interbedded clay and semi-consolidated conglomerate. Such deposits may represent the Salt Lake Formation, but this cannot be confirmed without examination of the cuttings.

Much of the Lake Mountains receives more than 12 inches per year (31 cm/yr) of precipitation (figure 10), the minimum value for recharge to aquifers to occur by direct infiltration of precipitation and snowmelt according to Feltis (1967). Water levels in the Cedar Valley basin-fill aquifer, however, slope toward the Lake Mountains, even within one mile (1.6 km) of bedrock exposures (figure 10). If ground water flowed from the Lake Mountains to the Cedar Valley basin fill as it does adjacent to the southern Oquirrh Mountains, water levels in Cedar Valley would slope away from the range and toward the valley center.

Table 3. *Transmissivity estimates for wells in basin-fill aquifer, Cedar Valley, Utah County[1].*

ID[2]	Location[3]	Depth to Bedrock (ft)	Well Diameter (in)	Static Water Level (ft)	Drawdown (ft)	Duration (hr)	Pumping Rate (gal/min)	Aquifer Thickness (ft)	Open Interval (ft)[4]	Storage Coefficient[5]	Transmissivity (ft^2/day)
41	S 20 E 1,300 NW 19 6S 1W	>590	16	227	109	64	1400	86	86	0.0012	3,794
1037	SE4 OF NW4 29 6S 2W	>654	16	-2	200	20	125	250	250	0.0012	124
22	S 310 W 550 N4 32 6S 2W	>30	8	8	2	9	20	30	30	0.0012	2,544
1039	S 608 E 1,300 NW 32 6S 2W	>613	16	-1	145	32	750	159	159	0.0012	1,275
1033	S 1,035 W 38 NE 18 6S 2W	462	16	164	32	24	1725	263	263	0.0012	28,506 [6]
1035	S 60 E 60 N4 20 6S 2W	>600	16	28	67	63	2400	117	117	0.0012	18,292
1120	S 100 E 50 NW 15 6S 2W	>475	16	119	134	33	515	650	650	0.0012	1,121

Notes

1. Calculations made using TGUESS (Bradbury and Rothschild, 1985).
2. Corresponds to labels on figure 16 and to ID column in table C.1.
3. Locations given in Point of Diversion notation - see figure C.2 for explanation.
4. Sum of screened linear feet.
5. Average of values reported by Feltis (1967, p. 15).
6. Using the method of Driscoll (1986), Van King of Stantec, Inc. (written communication, September, 2003) estimated the transmissivity of this well as 11,420 ft^2/day.

Possible explanations for this apparent contradiction between water-level gradients in Cedar Valley and recharge in the Lake Mountains include the following:

(1) More than 12 inches per year (31 cm/yr) of precipitation may be required to allow sufficient infiltration to induce recharge. If this hypothesis is correct, then the total amount of water available for recharge to the Cedar Valley basin-fill and bedrock aquifers is less than Feltis' (1967) estimate of 24,000 acre-feet per year (30 hm^3/yr). Calculations by Feltis (1967, p. 11, his table 1) suggest that if recharge occurs in areas with 16 inches (41 cm) or more of annual precipitation, the water available for recharge is about 20,500 acre-feet per year (25 hm^3/yr).

(2) A subsurface ground-water barrier along the range front may prevent ground-water flow from bedrock to the basin-fill aquifer. The most likely candidate for such a barrier is the concealed Lake Mountains normal fault.

(3) Ground-water flow in bedrock of the Lake Mountains is controlled by the structure of the Lake Mountains syncline, as proposed by Feltis (1967). If bedrock in the Lake Mountains was isotropic with respect to hydraulic conductivity, ground-water flow would follow the topographic gradient and some recharge would occur along the western margin of the Lake Mountains. Alternatively, high hydraulic conductivity parallel to bedding planes may direct flow toward the Lake Mountains syncline hinge line and away from Cedar Valley. Even so, hydraulic conductivity in the Lake Mountains syncline hinge line may be low compared to anticlinal hinges in anticlines and uniformly dipping areas, due to closure of joints (Huntoon, 1993).

Insufficient data exist to fully test these hypotheses.

Cross section C-C′ (plate 2) indicates that the central part of the Lake Mountains fault cuts middle to lower Paleozoic units and soles into a thrust ramp at depth. Fractures adjacent to these normal faults may enhance ground-water flow parallel to the fault planes (Caine and others, 1996). Displacement of the shale-rich middle and lower members of the Great Blue Formation likely created clay-rich gouge and "smears" of mudstone along the fault planes, features that would inhibit ground-water flow perpendicular to the fault plane. Based on this geologic reasoning, the Lake Mountains fault may act as a barrier or retardant to east-west ground-water flow and as a conduit for north-south and vertical ground-water flow. These suggestions should be regarded with caution, because (1) exposures of the fault planes are not available to observe fault-related structures, and (2) cross section C-C′ in this area is not well constrained, so the subsurface geometry may be different than depicted.

The basin-bounding normal faults in northwestern Cedar Valley cut the lower member of the Butterfield Peaks Formation, composed of interlayered quartzite and limestone and minor mudstone (cross section C-C′, plate 2). The mudstone may form smears along the fault plane, so the faults may retard ground-water flow transverse to their planes where they cut bedrock. These faults have no surface expression, and it is unknown whether they cut the lower part of the Quaternary basin fill.

Fairfield Spring

Fairfield Spring issues from the toe of the Manning Canyon alluvial fan west of the town of Fairfield (figures 3 and 17) and, as noted above, is an important source of culinary and irrigation water for west-central Cedar Valley. Recharge to Fairfield Spring originates in the Manning Canyon drainage basin in the southern Oquirrh Mountains as snowmelt and precipitation that infiltrate to the water table in bedrock (Feltis, 1967). This ground water likely enters the basin fill at the base of the upper part of the Manning Canyon alluvial fan, as suggested by Feltis (1967).

Fairfield Spring likely owes its location in part to the decrease in hydraulic conductivity within the transition zone from alluvial-fan to lakebed deposits. Retardation of ground-water flow in this transition zone may force water levels to near the ground surface. An alternative explanation is that a subsurface fault just east of the spring forms a ground-water barrier that localizes the spring. The lack of springs and seeps along the entire length of the Manning Canyon alluvial-fan margin suggests, however, that ground-water retardation due to a facies change and/or a fault is not the only factor localizing Fairfield Spring. A pre-existing topographic low and/or a gravel-filled alluvial channel below the surface may focus ground-water flow to Fairfield Spring.

Pumping of two privately owned irrigation wells (IDs 44 and 1035, table C.1), located about 2 miles (3 km) north-northeast of Fairfield Spring, decreases the flow of Fairfield Spring and was the subject of litigation in the early 1960s. Records from the Utah Division of Water Rights (figure 18) show that during 1963, spring flow decreased from about 3.8 to 1.9 cubic feet per second (108-54 L/sec) from mid-May to mid-July while the irrigation wells were pumped continuously, increased to about 2.5 cubic feet per second (71 L/sec) from mid-July to mid-August when the irrigation wells were pumped less than 12 hours per day, then flow recovered to about 3.9 cubic feet per second (110 L/sec) by the end of December after pumping ceased. Pumping rates were not reported. The relatively long distance and short time response of this interference suggests that a high-hydraulic-conductivity connection exists between Fairfield Spring and the irrigation wells.

Possible explanations for this hydrologic connection include pressure-gradient effects and a subsurface fault. Ground water in and east of the alluvial-fan toe is under confined conditions, making it more sensitive to pressure variations over long distances compared to unconfined conditions. The contrast in hydraulic conductivity at the interface between alluvial-fan and lakebed deposits may result in strong pressure communication in ground water along and directly west of the boundary. Drawdown at the irrigation wells may reduce the horizontal component of the pressure gradient between the wells and Fairfield Springs, resulting in decreased flow at the springs. This would result in hydro-

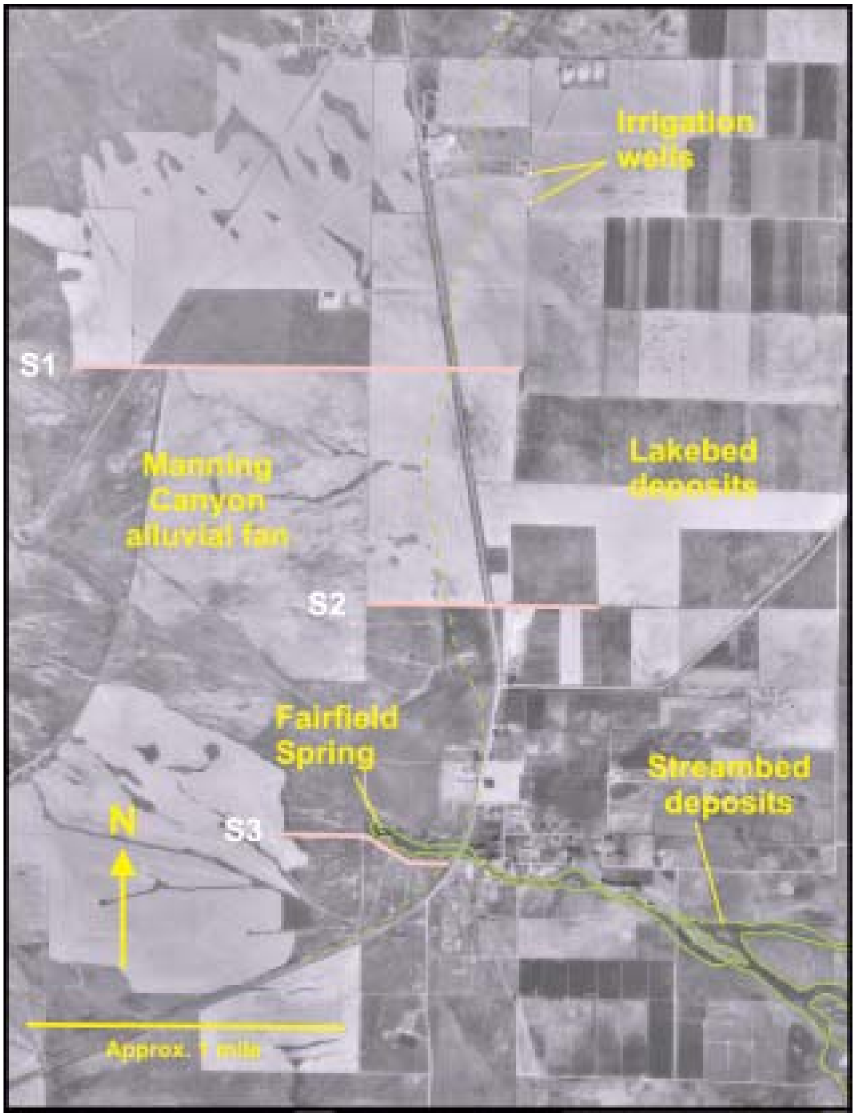

Figure 17. *Aerial photograph of west-central Cedar Valley, showing Fairfield Spring, irrigation wells, seismic-refraction line locations, and surficial deposits. The contacts between surficial deposits are in green. The contact between the Manning Canyon alluvial fan and lakebed deposits is gradational. Seismic-refraction lines labeled S1, S2, and S3. Base is a U.S. Geological Survey digital orthophotograph obained from the Utah AGRC (2001).*

logic communication, but not ground-water flow, roughly perpendicular to the local hydraulic gradient.

Drillers' logs for water wells show that the basin-fill sediment in the Fairfield Springs area consists chiefly of sandy to silty gravel, sand, and clay, interlayered at intervals of 10 to 20 feet (3-6 m) (cross sections G-G′ and J-J′, plate 3). Individual layers are lens-shaped, and typically at most 2 miles (3.2 km) wide. This array of intercalated gravel, sand, and clay layers becomes progressively finer grained to the east, reflecting the transition from dominantly distal alluvial-fan to dominantly lacustrine depositional environments. The position of the lake shoreline or playa (when present), and therefore the location of the facies transition, fluctuated during Quaternary time, so is at different positions at different depths. Ground water in this area likely resides in all of these sediment types but is under varying pressure conditions depending on depth and local stratigraphy. The drillers' logs indicate that the static water level in wells in the area varied from about 30 feet (9 m) below to 9 feet (3 m) above the land surface at the time of drilling. Only three well logs, including the two irrigation wells, contain information about the depth at which water was first encountered. In these wells the first water was encountered at 57 to 95 feet (17-29 m). This may represent a semi-confined water table or a shallow water table that is isolated from the deeper, confined aquifer whose potentiometric surface is near the land surface.

Dr. Ken Cook, in testimony as an expert witness for the legal case (*in* Anderson, 1972), suggested that Fairfield Spring and the irrigation wells are connected by a north-northeast-striking, east-side-down fault having high strike-parallel hydraulic conductivity. The fault, in his view, juxtaposes low-transmissivity basin-fill deposits in its hanging wall against higher transmissivity deposits in its footwall. Cook relied on gravity data for his interpretation, but did not specify the data source. This conclusion is difficult to evaluate because available gravity data for the area seem too widely spaced to interpret or locate a fault in the area of interest, and it is not known whether Cook collected or had access to a more detailed data set for the Fairfield Spring area.

Surficial evidence for a fault near Fairfield Spring and the irrigation wells is lacking. The proposed fault would be about 1.5 miles (2.4 km) from the valley-mountain boundary, suggesting that it is not a major basin-bounding fault if it exists. Cross section J-J′ (plate 3) trends north-south and

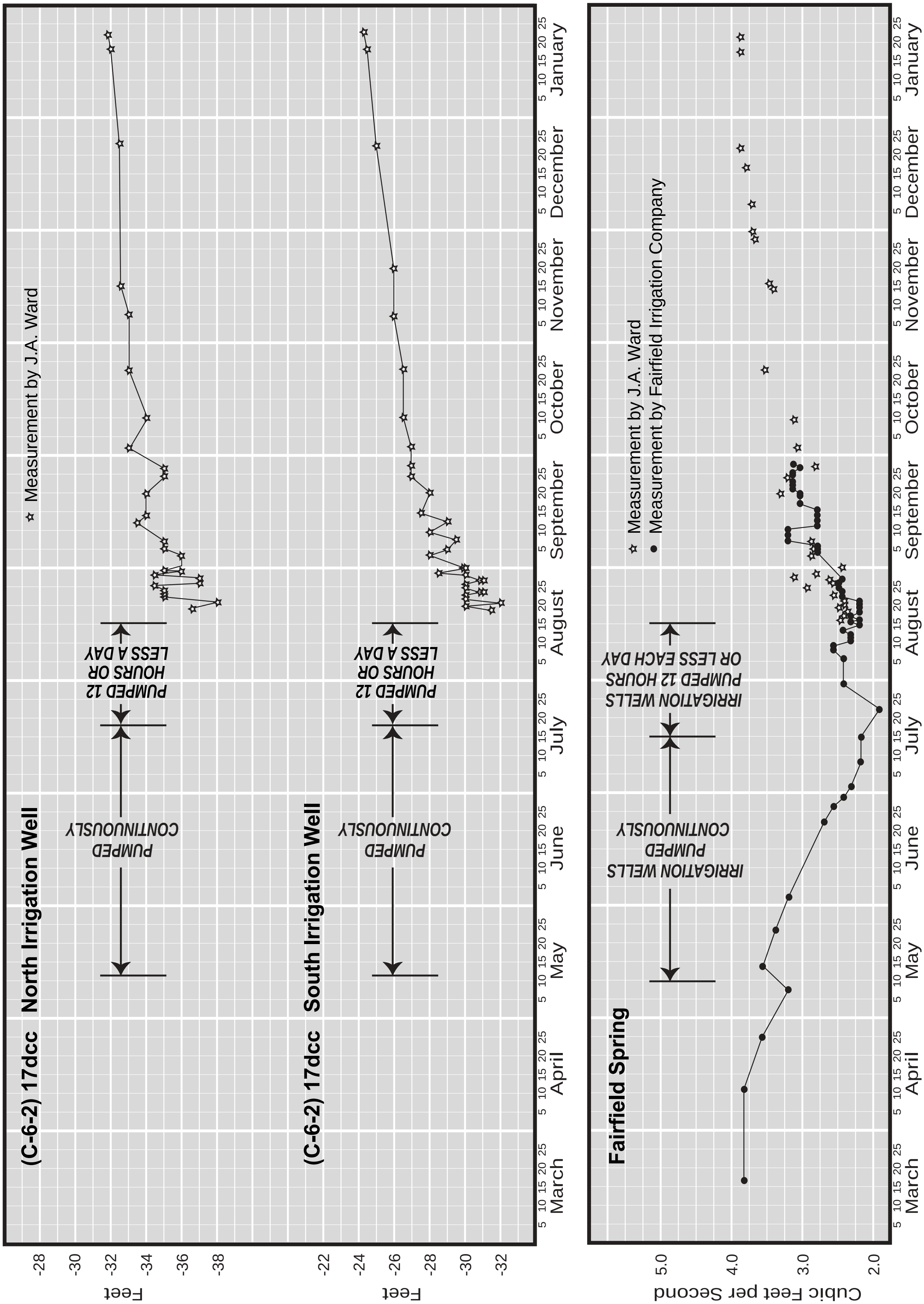

Figure 18. *Flow records for irrigation wells and Fairfield Spring, 1963-1964 (data from Utah Division of Water Rights unpublished files).*

includes the irrigation wells and wells about 0.25 miles (0.4 km) east of Fairfield Spring, and cross section H-H′ (plate 3) trends east-west and crosses Fairfield Spring. Neither section shows faults that could enhance the hydrologic connection between Fairfield Spring and the irrigation wells, but the accuracy of the water-well logs is limited. East-side-down faults cutting bedrock, delineated from water-well logs on cross sections F-F′ and G-G′ (plate 3), project west of Fairfield Spring.

To investigate the existence and location of a possible fault connecting Fairfield Spring and the irrigation wells, we conducted a reconnaissance seismic-refraction survey of the intervening area (figure 17; figure D.1, appendix D). The survey consisted of three linear, east-west traverses that crossed an imaginary line between Fairfield Spring and the irrigation wells. Each traverse was composed of several reversed refraction lines arranged end-to-end. See Appendix D for descriptions of the theory, methods, and results of the seismic-refraction survey. All three traverses show an upper layer that has low seismic-wave velocity, is 20 to 100 feet (6-30 m) thick, and has a relatively smooth, gently east-sloping base. In the northern traverse (S1, figures D.1 and D.2), the upper layer overlies high-velocity bedrock in the western third of the traverse and a middle, intermediate-velocity layer in the eastern two-thirds of the traverse. The other two traverses (S2 and S3, figures D.1, D.3, and D.4) show the upper and middle layers, with similar velocity structure, geometry, and depth to the velocity discontinuity shown in the eastern two-thirds of the northern traverse.

Our seismic-refraction survey yielded no evidence for a fault connecting Fairfield Spring and the irrigation wells within the upper 200 feet (60 m) of the basin fill. A pre-late Quaternary fault may exist below the depth sampled by our seismic-refraction survey. Because this fault, if it exists, has no surface expression, location of the irrigation wells along its trace would be highly coincidental. Hydrologic communication due to a reduced pressure gradient along the alluvial-fan margin is a less serendipitous explanation, but the connection would have to occur not only over 2 miles (3.2 km) distance but also from a 400- to 600-foot (120-180 m) depth range (the screened interval of the irrigation wells) to the land surface. Neither explanation is entirely satisfactory. A carefully planned and monitored aquifer test in the area would likely improve our understanding of this interference problem.

STRUCTURE AND HYDROGEOLOGY OF BEDROCK UNITS

Introduction

Bedrock aquifers are important to the hydrogeology of Cedar Valley because: (1) recharge to the basin-fill aquifer originates as infiltration to bedrock in the adjacent mountain ranges (Feltis, 1967); (2) new water development in the basin is primarily in bedrock aquifers; (3) subsurface outflow to Utah Lake occurs within bedrock; and (4) several springs used for water supply emanate from bedrock (table 1).

Most new wells in Cedar Valley are in the Eagle Mountain City-Cedar Pass area in the northeast part of the valley, and many of these wells are screened in bedrock. Eagle Mountain City reports withdrawals from five municipal-supply wells located in the northwestern and north-central part of Cedar Valley, one of which is screened in bedrock (Montgomery Watson, 2000). Eagle Mountain City recently drilled four test wells in the Cedar Pass area; these wells are between 1,000 and 2,000 feet (300-600 m) deep and are all screened in bedrock. These test wells indicate that future ground-water development in northern Cedar Valley will likely focus on bedrock aquifers (T. Jarvis, Montgomery Watson Harza, verbal communication, 2002).

Hydrostratigraphy

Hydrostratigraphy involves grouping sediments and rocks into hydrostratigraphic units based on their ability to store and transmit ground water. A hydrostratigraphic unit is a set of rocks or sediment having similar water-bearing properties, and may comprise all or part of a single geologic formation or several formations grouped together. In this report, hydrostratigraphic units are defined by their water-bearing properties where known, and by lithology where hydrologic data are absent.

Table 4 and figure 8 summarize the hydrostratigraphy of bedrock units in the Cedar Valley study area. The hydrogeology of the basin fill was discussed in a previous section. Based on lithology, the Tertiary volcanic heterogeneous aquifer may have hydrogeologic properties intermediate between those of unconsolidated sediment and fractured bedrock. The Salt Lake Formation consists primarily of stratified clayey siltstone that likely functions as an aquitard. Some deep wells in the valley center, however, may draw water from sandstone and conglomerate near the base of the Salt Lake Formation (cross sections F-F′, G-G′, H-H′, and J-J′, plate 3). Tertiary volcanic rocks exposed on the margins of Cedar Valley consist primarily of poorly sorted, semiconsolidated pyroclastic breccia having widely spaced joints and faults. This rock is probably a low-transmissivity bedrock aquifer.

The Oquirrh Group heterogeneous aquifer adjacent to and beneath Cedar Valley consists of the West Canyon Limestone and the lower unit of the Butterfield Peaks Formation (table 4). Limestone, quartzite, and sandstone in these units have moderate to high fracture density; mudstone layers are relatively rare and thin. Feltis (1967, p. 12) suggested that solution channels in carbonate rocks of the Oquirrh Group enhance ground-water flow. Although this is a reasonable suggestion, no direct evidence for such features has been documented. Younger formations of the Oquirrh Group crop out in the northeastern part of the study area (plate 1) and are considered part of this aquifer, but are absent adjacent to and beneath Cedar Valley. Two test wells for Eagle Mountain City are screened in the Oquirrh Group heterogeneous aquifer (IDs 1011 and 1126, table 2).

The Great Blue Limestone consists of two main limestone aquifers separated by a shale sequence that is up to 850 feet (260 m) thick (figure 8; table 4). Two test wells for Eagle Mountain City drew water from the upper Great Blue Limestone aquifer (IDs 156 and 1125, table 2). Development tests indicated that well 156 could yield 2,200 gallons per minute (8,300 L/min) under long-term use, and indicated a transmissivity of 15,500 ft^2/day (1,440 m^2/d) and a hydraulic conductivity of 37 ft/day (11 m/d) (Montgomery Watson,

Table 4. *Definition and characteristics of hydrostratigraphic units in Cedar valley, Utah County study area.*

Hydrostratigraphic Unit	Geologic Map Unit(s)[1]	Thickness[1] in feet (m)	Lithology	Hydrologic Properties	Production	Notes
Unconsolidated aquifer	All Quaternary units	0-2,000 (0-610)	Poorly to moderately sorted boulder gravel interbedded with lakebed clay, silt, and sand	Gravel and sand have highest porosity, permeability, and hydraulic conductivity	Presently the main aquifer in Cedar Valley	Gravel is more common along valley margins
Salt Lake Formation aquitard	Tsl	0-400+ (0-122+)	Mudstone and minor limestone, sandstone, and conglomerate	Aquitard; volumetrically minor sandstone and conglomerate may yield some water	None known	May underlie unconsolidated deposits below parts of Cedar Valley
Tertiary heterogeneous igneous-rock aquifer	Tio, Tvo, Tie, Tve	0-5,200+ (0-1,580+)	Pyroclastic breccia, mudflow breccia, flow rock, and intrusive rock	Semiconsolidated breccia and fractured flows and intrusive masses are the best prospective aquifers	Likely yields water to mines in East Tintic district	May underlie unconsolidated deposits below parts of Cedar Valley
Oquirrh Group heterogeneous carbonate-quartzite aquifer	IPbmm, IPbmc, IPbpu, IPbpl, IPwc, IPo	IPbmm, IPbmc, IPbpu combined: 12,700 (3,860) IPbpl, IPwc combined: 6,160 (1,880)	Interbedded quartzite, sandstone, limestone, and minor mudstone	Fractured-bedrock aquifer; solution widening of joints and bedding planes in limestone possible but undocumented	lPbpl yields water to Cedar Pass test wells #1 and #4 (IDs 1011 and 1126, tables 2 and C.1)	lPbpl and lPwc are exposed throughout study area; other units present only in NE corner of map area
Manning Canyon aquitard	IPMmc	1,200-1,560 (365-475)	Mudstone with sparse quartzite and limestone	Aquitard	None known	-
Great Blue heterogeneous aquifer	Mgb	2,530 (770)	Platy to thick-bedded limestone; mudstone in middle part and lowest 100 feet (30 m)	Lower and upper parts are fractured-bedrock aquifers; middle part and lowest 100 feet (30 m) are aquitards	Yields water to Cedar Pass test wells #2 and #3 (IDs 1125 & 156, tables 2 and C.1), and petroleum-exploration well OW6 (table C.2)	Shown only on southern half of the Lake Mountains where Great Blue Limestone is undivided

Table 4. *(continued)*

Upper Great Blue aquifer	Mgbu	600 (185)	Platy to thick-bedded limestone	Fractured-bedrock aquifer; solution widening of bedding planes and joints possible but undocumented	Yields water to Cedar Pass test wells #2 and #3 (IDs 1125 & 156, tables 2 and C.1), well n1003 (Mower, 1997), and petroleum-exploration well OW6 (table C.2)	-
Long Trail aquitard	Mgbm	850 (260)	Calcareous mudstone	Aquitard	-	-
Lower Great Blue aquifer	Mgbl	980 (300)	Thick-bedded limestone	Fractured-bedrock aquifer; solution widening of bedding planes and joints possible but undocumented	Yields water to Cedar Pass test well #3 (ID 156, tables 2 and C.1) and petroleum-exploration well OW6 (table C.2)	-
Lower Great Blue aquitard	Mgbl	0-100 (0-30)	Calcareous mudstone	Aquitard	-	Present only in subsurface of eastern half of study area
Middle Paleozoic carbonate aquifer	Mh, Md, Mg, Mf, MDpv, upper part of DSOu	3,425-4,545 (1,045-1,385)	Limestone and dolomite; interbedded with quartzite in Humbug Formation	Fractured-bedrock aquifer; solution widening of bedding planes and joints possible but undocumented	Yields water to petroleum-exploration well OW6 (table C.2); may yield water to mine shafts in East Tintic district	Good potential aquifer in anticline crests in Cedar Pass area
Opohonga aquitard	lower part of DSOu	800 (245)	Clay-rich limestone	Possibly a leaky aquitard – contains some fractures	Unknown	Not differentiated on plate 1

Table 4. *(continued)*

Lower Paleozoic carbonate aquifer	ɭ u	2,750 (840)	Limestone and dolomite	Fractured-bedrock aquifer; solution widening of bedding planes and joints possible.	None in Cedar Valley study area; may yield water to mine shafts in East Tintic district	-
Ophir aquitard	ɭ o	430 (130)	Shale and quartzite	Aquitard	-	-
Cambrian-Proterozoic quartzite aquifer	ɭ t, pɭ b	4,025-4,875+ (1,225-1,485)	Quartzite	Fractured-rock aquifer	None in Cedar Valley study area; may yield water to mine shafts in East Tintic district	-

Notes
- No data or comment.
1. Geologic map units shown on plate 1 and figure 7, and described in appendix A.

2000). A water well in the northern part of Cedar Pass (well 1003, table C.1), in the Great Blue Limestone aquifer, was expected to yield about 320 gallons per minute (1,211 L/min) during normal production; tests indicated a transmissivity of 98 ft^2/day (9 m^2/d) and a hydraulic conductivity of 1.03 ft/day (0.3 m/d) (Mower, 1997). A petroleum-exploration well (well OW6, table C.2) yielded 2 to 4 cubic feet per second (57-113 L/sec) of water from the two Great Blue aquifers and the Mississippian Humbug Formation (Wells, 1962).

The middle Paleozoic carbonate aquifer (figure 8) is composed of interbedded limestone and dolomite, and is likely a good fractured-bedrock aquifer. These units are at least 2,000 feet (610 m) below the surface in all but the southern part of the study area. The underlying Cambrian-Proterozoic quartzite aquifer (figure 8) is also a good prospective fractured-bedrock aquifer, and is at or near the surface only in the southern part of the study area.

Structural Geology

Introduction

Rocks in the study area were deformed during Late Jurassic to early Tertiary time in the Idaho-Wyoming-Utah segment of the Sevier orogen and during late Tertiary time by Basin and Range normal faults (Royse 1993; Stewart, 1998), resulting in a complex structural geometry. These structures and their possible influence on ground-water flow are described in this section.

Folds

Sedimentary layering in pre-Tertiary bedrock in the study area is deformed into large- and small-scale folds (figure 7; plate 1; cross sections A-A′ through D-D′, plate 2). The hinge lines of almost all of these folds trend northwest, reflecting northeast-directed shortening. Several large-amplitude folds are exposed in the southern Oquirrh Mountains and the Traverse Mountains north of Cedar Valley (plate 1). The North Tintic anticline in the East Tintic Mountains exposes in its hinge zone the oldest stratigraphic units and deepest structural levels in the study area.

Faults

Faults in the study area formed during Late Jurassic to early Tertiary shortening, mid-Tertiary igneous activity, and late Tertiary-Quaternary Basin and Range normal faulting. Thrust and reverse faults are exposed in the Traverse Mountains, at the west-central base of the Lake Mountains, and in the northeastern East Tintic Mountains (plate 1). Northeast-striking transcurrent faults in the East Tintic Mountains and Mosida Hills cut fold axes and thrust faults, and are cut by late Tertiary normal faults. These strike-slip faults likely formed as tear faults during shortening (Proctor, 1959; Morris, 1964a, 1964b). Some normal faults in the East Tintic Mountains and Traverse Mountains formed during igneous activity and are in part responsible for localizing intrusion of dikes and associated mineralization (Morris, 1964a, 1964b; Babcock and others, 1997). Basin and Range normal faults in Cedar Valley strike north to northeast, were active from middle or late Miocene through middle Quaternary time, and delineate the modern valleys and ranges (Stewart, 1998).

Joints and Cleavage

Joints are pervasive at low to moderate density (average trace lengths of 1 to 10 feet [0.3-3 m], and average spacing of about 3 inches [8 cm] to 3 feet [1 m]) in all pre-Tertiary units designated as aquifers (table 4) in this study. Most rocks have three joint sets: (1) northwest- to north-striking, parallel to local and regional fold hinges, (2) northeast- to east-striking, and (3) parallel to bedding planes. Joint density typically increases near fold axes, but systematic joint surveys to quantify this observation were not performed as part of this study. Mudstone units, including the Manning Canyon Shale and the middle member of the Great Blue Limestone, lack joints. Joints are sparse in Tertiary volcanic breccia and in the Salt Lake Formation, and are moderately dense in flow rocks.

Cleavage is a planar rock fabric manifested as fine-scale parting surfaces, formed along dissolution surfaces or by preferred orientation of platy mineral grains. Paleozoic limestone and dolomite units exposed in the Mosida Hills and eastern Lake Mountains contain north- to northwest-striking cleavage. The cleavage strikes parallel to local fold axes, and likely formed during folding. No systematic study of cleavage was made as part of this study, so the details of variations in orientation and density are not known.

Discussion - Structural Controls on Ground-Water Flow

The structures discussed above may influence ground-water flow in the Cedar Valley study area by providing high-conductivity pathways or, in some cases, barriers, and by controlling the subsurface geometry and position of the aquifers. The discussion that follows is based solely on evaluation of these structures in terms of principles of ground-water flow in fractured rock; no hydrogeologic data, other than high yields to wells in bedrock discussed above, exist to confirm these hypotheses. Folds likely accommodate ground-water flow parallel to their axes, most strike-slip and thrust faults accommodate ground-water flow parallel to their planes but act as barriers to transverse flow, and the hydrogeologic properties of normal faults may be highly variable.

Joints in Cedar Valley bedrock aquifers form well-connected, three-dimensional networks. Joint planes in quartzite and sandstone are smooth and unmineralized, whereas some joints in carbonate rocks are lined with fine-grained calcite. These features suggest that joints accommodate significant ground-water flow in bedrock aquifers, especially quartzite and sandstone, in the study area. Reconnaissance field observations yielded no direct evidence for solution widening of joints, but such features may exist at depth, especially where thermal waters are present as in petroleum-exploration well OW6 (table C.2) (Wells, 1962).

Faults are poorly exposed in the study area, so their hydrogeologic properties are difficult to determine with confidence. A northeast-striking fault that likely formed as a tear fault during late Mesozoic-early Cenozoic regional shortening is exposed on Topliff Hill in the southwestern part of the study area. The fault plane is sealed by calcite veins and would likely be a barrier to ground-water flow transverse to its plane. The rock mass adjacent to the fault plane is densely jointed, and some, but not all, of these joints are filled by calcite veins. The unfilled joints may accommodate fault-parallel ground-water flow at depth. If this exposed fault is analogous to other faults cutting carbonate bedrock in the study area, these faults likely accommodate ground-water flow parallel to their planes and act as barriers perpendicular to their planes. Thrust faults having large displacement likely develop fine-grained gouge along their slip planes and act as barriers to ground-water flow (Caine and others, 1996).

The hydrogeologic properties of normal faults in the study area may vary depending on the amount of displacement and the types of lithology that they cut (Caine and others, 1996). For example, the Lake Mountains fault likely acts as a barrier to horizontal ground-water flow along its central part, comprising about half of its total trace length, but may permit cross-fault flow along its northern and southern parts, each comprising roughly one-quarter of the fault's trace length. Ground-water levels in the basin fill of east-central Cedar Valley suggest that the central part of the Lake Mountains normal fault prevents subsurface flow between Lake Mountains bedrock and the basin fill, as discussed earlier in the section, "Hydrologic connection between basin fill and bedrock." This part of the Lake Mountains fault likely acts as a barrier to horizontal ground-water flow due to the combined effects of clay smears along the fault plane derived from the Manning Canyon Shale, and fine-grained fault-zone material having low permeability.

Montgomery (1995) cited a transmissivity value of 93,583 ft^2/day (8,694 m^2/day) for the Eagle Mountain City supply well on the west-central margin of the Lake Mountains, and attributed this very high value to flow parallel to the Lake Mountains fault plane. His data and conclusions are consistent with the ideas about fault-zone permeability presented here.

The northern and southern parts of the Lake Mountains fault may not, however, act as significant barriers to horizontal ground-water flow. There, the fault cuts the lower member of the Butterfield Peaks Formation, which is composed chiefly of limestone and quartzite, in both its hanging wall and footwall. Based on the shale-poor composition of the lower member of the Butterfield Peaks Formation, the Lake Mountains fault probably does not have significant clay-rich smears that would impede ground-water flow along its northern and southern parts.

Faults that act as barriers to horizontal ground-water flow may accommodate flow parallel to their planes (Caine and others, 1996). Geothermal springs such as Saratoga Springs along the western shore of Utah Lake probably issue from normal faults and result from fault-parallel flow. Montgomery (1995) suggested that some of the water entering well 1018 (tables 2 and C.1) on the west-central margin of the Lake Mountains has risen along the Lake Mountains fault.

Ground-water flow may preferentially follow bedding planes in the Oquirrh, Great Blue, and middle Paleozoic carbonate aquifers (table 4); interbedded low-permeability rocks such as mudstone may magnify this effect by retarding flow normal to bedding. Ground-water flow in fractured-bedrock aquifers having significantly tilted bedding follows complicated local flow paths; the regional flow direction depends mainly on the regional head gradient.

Folds may influence ground-water flow by their geometry and by spatial variations in fracture density. Ground water may preferentially flow away from anticlinal axes and toward synclinal axes due to the influence of inclined bedding in fractured bedrock described above. Fracture density increases in the axes of many folds, creating higher secondary permeability, and joint aperture and solution widening may be especially favorable in anticlinal axes (Huntoon, 1993). Fold axes may, therefore, be preferred ground-water flow paths, especially in anticlines. The west limb of the Lake Mountains syncline may divert recharge on the west side of the range toward the syncline hinge line and away from Cedar Valley, as discussed in a previous section.

In pre-Tertiary bedrock exposed in the Mosida Hills and southern Lake Mountains, fold axes, bedding, joints, and cleavage strike northwest to north, and most faults strike northeast (plate 1; cross section D-D′, plate 2). These features likely combine to produce complicated local ground-water flow paths in bedrock below the Mosida Hills, but define an overall northwest-southeast preferred flow direction. This structurally defined preferred flow direction is parallel to the southeast-directed water-level gradient (albeit poorly defined) in southeastern Cedar Valley. Bedrock structures, therefore, likely accommodate southeast-directed subsurface underflow from Cedar Valley to Utah Lake below the Mosida Hills and southern Lake Mountains.

The ground-water surface in the Cedar Valley basin fill slopes toward the central Lake Mountains to within 0.5 mile (0.8 km) of the mountain front (figure 3), which led Feltis (1967) to suggest that subsurface outflow may exit Cedar Valley below the Lake Mountains. Dustin and Merritt (1980), however, observed no freshwater seeps on the western shore of Utah Lake east of the Lake Mountains. Limited well and structural information also indicate that subsurface flow below the Lake Mountains may be minimal. A water well on the west-central flank of the Lake Mountains completed in the Manning Canyon Shale and upper member of the Great Blue Limestone, drilled to 843 feet (255 m) depth, was dry (well 1021, table C.1; Wallace, 2002). Based on this datum, ground water apparently does not cross from the Cedar Valley basin fill into bedrock below the central Lake Mountains.

Recharge entering the Oquirrh Group aquifer above the 12-inch precipitation contour on the Lake Mountains (figure 3) likely remains perched above the Manning Canyon Shale. Bedding-parallel flow carries the ground water toward the Lake Mountains syncline hinge line, then preferentially flows north or south parallel to the hinge line and enters the basin-fill deposits west of Utah Lake, as Feltis (1967) suggested. Some of this recharge to the western Utah Lake basin fill may contribute to the freshwater seeps observed by Dustin and Merritt (1980) in Goshen Bay. If this flow path exists, it represents a source for seeps along western Utah Lake in addition to underflow from the Cedar Valley basin. This may partly resolve the difficulty presented by the fact that the estimate of inflow to Utah Lake in Goshen Bay by Dustin and Merritt (1980) is such a high percentage of Feltis' (1967) estimate of available recharge to the Cedar Valley basin.

Fold axes, faults, and bedding in the northern Lake Mountains – Cedar Pass area strike northwest (plate 1; cross sections A-A′ and B-B′, plate 2). Surficial deposits in this area are thin in most places, so ground water resides primarily in the upper Great Blue Limestone and Oquirrh Group aquifers (table 4; cross sections A-A′, B-B′, plate 2, and E-E′, plate 3). The bedrock structure and stratigraphy in the northern Lake Mountains – Cedar Pass area likely accommodate southeast-directed underflow from northeastern Cedar Valley toward northern Utah Lake and the Jordan River. Feltis (1967) showed steeply south-sloping ground-water gradients in the Cedar Pass area (figure 3), defined only by two wells on either side of Cedar Pass. Based on significantly more data, Mower (1997) showed east- to northeast-sloping water-level contours in the Cedar Pass area. Ground-water levels probably vary in a complex way locally, and more data are required to better define gradients and evaluate subsurface underflow in this area.

SUMMARY AND CONCLUSIONS

Quaternary to early Tertiary basin-fill sediments of Cedar Valley are presently the principal aquifer for the valley. Alluvial-fan deposits along the valley margins grade to and are interbedded with lacustrine deposits in the basin center. Clayey siltstones of the Tertiary Salt Lake Formation and older volcanic breccia may underlie the basin-fill deposits. The basin fill is locally over 2,000 feet (600 m) thick below the northern valley center, and isopach contours of the basin fill form a roughly symmetrical ellipse having a north-south-trending long axis centered over the northern part of the valley.

Ground water is confined down gradient of the transition from alluvial-fan to lakebed deposits. The hydrologic connection between basin-fill deposits and bedrock is likely poor in the basin center, due to intervening low-permeability deposits, and locally good along the basin margins where alluvial fans directly overlie bedrock. The Lake Mountains fault is probably a barrier to ground-water flow transverse to its plane along its central part. Strong hydrologic connection between Fairfield Spring and irrigation wells to the north occurs along a facies boundary at the toe of an alluvial fan or a concealed, north-striking fault. A detailed aquifer test in the area should be conducted to better understand the nature and magnitude of this hydrologic connection.

The Utah Department of Agriculture and Food collected twenty-three new water-quality samples from wells in northern Cedar Valley in October 2001, to confirm chemical trends observed in 29 samples reported by Feltis (1967). Total-dissolved-solids concentrations were similar but higher in the new samples, and these samples displayed similar geographic trends in composition. Ground-water quality is good in the northwestern part of Cedar Valley adjacent to the southern Oquirrh Mountains, the principal recharge source for the basin-fill aquifer; ground water there is calcium-bicarbonate type having total-dissolved-solids concentrations less than 1,000 mg/L. The quality of ground water in the basin-fill aquifer degrades as it migrates to the east and southeast, primarily due to chemical reactions with clay-rich lacustrine sediment. In the northeastern part of Cedar Valley, total-dissolved-solids concentrations range from about 400 to 1,200 mg/L and the water is enriched in sodium and chloride relative to water in the northwestern part of the valley. Water migrating upward along the Lake Mountains fault may also affect ground-water quality in northeastern Cedar Valley. In the southeastern part of Cedar Valley, total-dissolved-solids concentrations range from about 1,400 to 2,000 mg/L and the ground water is enriched in sodium and sulfate compared to the northwestern part of the valley. The increased sulfate concentration may result from chemical reactions with Tertiary sulfide-bearing sediment and/or volcanic tuff.

Fractured Paleozoic limestone and quartzite form bedrock aquifers beneath and adjacent to Cedar Valley. The Pennsylvanian Oquirrh Group, the upper and lower members of the Mississippian Great Blue Limestone, and the Mississippian Humbug Formation are the best aquifers with respect to production and water quality. The Mississippian-Pennsylvanian Manning Canyon Shale and the middle member of the Mississippian Great Blue Limestone form significant aquitards within the upper to middle Paleozoic section.

Structures in bedrock along the southeastern and northeastern boundaries of Cedar Valley facilitate southeast-directed ground-water flow from Cedar Valley to Goshen Bay and east to northeast-directed flow to northwestern Utah Lake and the Jordan River (Hunt and others, 1953; Feltis, 1967; Dustin and Merritt, 1980; Mower, 1997; T. Jarvis, written communication, 2003). Northwest-striking anticlines and faults form ground-water flow pathways for this underflow. The Lake Mountains fault may form a barrier to underflow below the Lake Mountains.

Bedrock and alluvial-fan aquifers along the northwestern margin of the valley are the best prospects for future ground-water development, because recharge is relatively high and ground-water quality is good, and ground-water pathways are more easily constrained here than in other parts of the basin. Due to regional ground-water flow patterns as presently understood, increased future ground-water withdrawals from bedrock aquifers in northwestern Cedar Valley and the southeastern Oquirrh Mountains would likely impact ground-water flow and supply in Cedar Pass and could decrease the amount of subsurface outflow to Utah Lake and the Jordan River. Increased future ground-water withdrawals from bedrock aquifers in the Cedar Pass area would also decrease the amount of subsurface outflow to Utah Lake.

ACKNOWLEDGMENTS

This project was funded by the Utah Division of Water Rights. Reviews by Todd Jarvis (Oregon State University), Van King (Stantec, Inc.), Sue Thiros (U.S. Geological Survey), Vanessa Brown (Utah Division of Water Rights), and Mike Lowe, Bob Biek, Mike Hylland, Kimm Harty, and Rick Allis of the Utah Geological Survey led to substantial improvements of the manuscript. Todd Jarvis (while at Montgomery Watson Harza, Inc. in 1999) provided unpublished hydrogeologic reports and cross sections with the permission of Eagle Mountain City, and shared his knowledge of the hydrogeology of the study area. Ken Krahoulec and Geoff Ballantyne of Kennecott Copper, Inc. provided an electronic copy of their geologic map of the Oquirrh Mountains, saving significant time at the digitizing table. Kim Nay (UGS) digitized the remaining sources of the geologic map on plate 1, and drafted the figures. Alison Corey, Matt Butler, and Bryan McCrory did GIS and layout work for plate 1 and the map-based illustrations.

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GLOSSARY

Definitions are from Jackson (1997) or Fetter (1994), with modification by the author. Many of the terms appear only in the Description of Map Units in appendix A. Italicized words in definitions may not appear in the text but are in the glossary.

Alkali feldspar – A group of *feldspars* composed of mixtures, or mixed crystals, of *potassium feldspar* and *sodium feldspar* in any ratio.

Alluvial – Deposited by a stream or other body of running water. Alluvium is a general term for unconsolidated *detrital* material deposited during comparatively recent geologic time by a stream or other body of running water, as sorted or semisorted sediment in the bed of a stream or on its flood plain or delta, or as a cone or fan at the base of a mountain slope.

Alluvial fan – A low, outspread, relatively flat to gently sloping mass of loose rock material, shaped like an open fan or segment of a cone, deposited by a stream at the place where it issues from a narrow mountain valley upon a plain or broad valley, or where a tributary stream is near or at its junction with the main stream, or wherever a constriction in a valley abruptly ceases or the gradient of the stream suddenly decreases.

Aluminosilicate – A silicate in which aluminum substitutes for the silicon in the SiO_4 tetrahedra.

Andesite – A dark-colored, fine-grained volcanic rock containing *phenocrysts* of Na-rich *plagioclase feldspar* and one or more of the following: *biotite*, *hornblende*, or *pyroxene*; in a *groundmass* composed generally of the same minerals as the *phenocrysts*.

Anticline – A *fold*, the core of which contains stratigraphically older rocks, and is convex upward.

Aperture – the width of a fracture opening measured perpendicular to the two rock surfaces on either side of the fracture (may be infilled).

Aquifer – A body of rock or sediment that contains sufficient saturated permeable material to conduct ground water and to yield significant quantities of water to wells and springs.

Aquifer test – A test made by pumping a well for a period of time and observing the change in hydraulic head in the aquifer. Typically, water levels are measured in one or more observation wells and the pumping well. An aquifer test may be used to determine the capacity of the well and the hydraulic characteristics of the aquifer.

Aquitard – An impermeable layer that creates confined ground-water conditions, in which ground water is under pressure significantly greater than that of the atmosphere.

Ash-flow tuff – A density-current deposit, generally a hot mixture of volcanic gases and tephra that travels across the ground surface; produced by the explosive disintegration of viscous lava in a volcanic crater, or from a fissure or group of fissures. The solid materials contained in a typical ash flow are generally unsorted and ordinarily include volcanic dust, *pumice*, *scoria*, and blocks in addition to ash.

Augite – A common mineral of the *clinopyroxene* group: $(Ca, Na)(Mg,Fe^{+2}, Al)(Si,Al)_2O_6$.

Biotite – A widely distributed rock-forming mineral of the *mica* group: $K(Mg,Fe^{2+})_3(OH)_2[(Al,Fe^{3+})Si_3O_{10}]$.

Bomb – A *pyroclast* that was ejected while viscous, received its rounded shape while in flight, has variable shape, may be vesicular to hollow inside, and is greater than 2.5 inches (64 mm) in diameter.

Breccia – A coarse-grained *clastic* rock composed of angular broken rock fragments held together by mineral cement or in a fine-grained matrix.

Calcite – A common rock-forming mineral – $CaCO_3$.

Carbonate – Sediment formed by the organic or inorganic precipitation from aqueous solution of calcium-, magnesium-, or iron-carbonate minerals.

Chert – A hard, dense, dull to semivitreous, *microcrystalline* or *cryptocrystalline* sedimentary rock, consisting dominantly of interlocking crystals of quartz less than about 30 microns in diameter, that may also contain impurities such as calcite, iron oxide, and the remains of siliceous and other organisms. It has a tough, splintery to conchoidal fracture, and may be variously colored. Chert occurs as nodular or concretionary segregations (chert nodules) in limestone and dolomites, or as areally extensive layered deposits (bedded chert); it may be an original organic or inorganic precipitate, or a replacement product.

Cherty – see *chert*.

Clastic – Pertaining to a rock or sediment composed principally of broken fragments that are derived from preexisting rocks or minerals and that have been transported some distance from their places of origin.

Cleavage – A locally planar fabric in an unmetamorphosed or weakly metamorphosed, fine-grained rock defined by either the tendency of a rock to split in a particular direction, a preferred orientation of crystal planes in mineral grains, or a preferred orientation of inequant grain shapes.

Clinopyroxene – A group name for *pyroxenes* crystallizing in the monoclinic system and sometimes containing considerable calcium with or without aluminum and the alkalies.

Colluvium – A general term applied to any loose, heterogeneous, and incoherent mass of soil material and/or rock fragments deposited by rainwash, sheetwash, or slow continuous downslope creep, usually collecting at the base of gentle slopes or hillsides.

Conglomerate – A coarse-grained *clastic* sedimentary rock, composed of rounded to subangular fragments larger than 2 mm in diameter typically containing fine-grained particles in the interstices, and commonly cemented by calcium carbonate, iron oxide, silica, or hardened clay; the consolidated equivalent of gravel.

Cordilleran fold and thrust belt – A gently arcuate, convex-east belt of thrust faults and related folds, extending from northern British Columbia to southeastern California and from the eastern boundary of the Cascade and Sierra Nevada Mountains to western Wyoming and central Utah, that formed during mid-Cretaceous through Paleocene time.

Cryptocrystalline – Said of a texture of a rock consisting of crystals that are too small to be recognized and separately distinguished even under the ordinary microscope (although crystallinity may be shown by the use of the electron microscope).

Detritus – A collective term for loose rock and mineral material that is worn off or removed by mechanical means, such as sand, silt, and clay, derived from older rocks and moved from its place of origin.

Dike – A tabular igneous intrusion that cuts across the bedding or *foliation* of the country rock.

Dip – The inclination of a planar surface (for example, bedding or a fault), as measured relative to horizontal and in a vertical plane that is perpendicular to the *strike* of the surface.

Dolomite – A *carbonate* sedimentary rock of which more than 50% by weight or by areal percentages under the microscope consists of the mineral dolomite, or a variety of limestone or marble rich in magnesium carbonate. The mineral dolomite has the chemical formula $CaMg(CO_3)_2$.

Evapotranspiration – The sum of evaporation plus *transpiration*.

Facies – The aspect, appearance, and characteristics of a rock unit, usually reflecting the conditions of origin; a mappable, areally restricted part of a *lithostratigraphic* body, differing in *lithology* from other beds deposited at the same time and in lithologic continuity.

Fault – A discrete surface or zone of discrete surfaces separating two rock masses across which one rock mass has slid past the other.

Feldspar – A group of abundant rock-forming minerals, generally divided into two compositional groups, (1) the *plagioclase feldspar* series: $CaAl_2Si_2O_8$ to $NaAlSi_3O_8$, and (2) the *alkali feldspar* series: $(K,Na)AlSi_3O_8$.

Feldspathoid – A group of comparatively rare rock-forming minerals consisting of *aluminosilicates* of sodium, potassium, or calcium having too little silica to form *feldspar*. Feldspathoids are chemically related to the feldspars, but differ from them in crystal form and physical properties; they take the places of feldspars in igneous rocks that are undersaturated with respect to silica or that contain more alkalies and aluminum than can be accommodated in the feldspars.

Felsic – A mnemonic adjective derived from *feldspar* + lenad (*feldspathoid*) + *silica*, and applied to an igneous rock having light-colored minerals in its mode; also, applied to those minerals (*quartz, feldspars*, *feldspathoids*, *muscovite*) as a group.

Fold – A curve or bend of a planar structure such as rock strata or bedding planes.

Foliation – A general term for a planar arrangement of textural or structural features in any type of rock, especially the locally planar fabric in a rock defined by a fissility, a preferred orientation of crystal planes in mineral grains, a preferred orientation of inequant grain shapes, or from compositional banding.

Footwall – The lower block of a non-vertical fault.

Gouge – A thin layer of soft, fault-comminuted rock material in the core of a fault.

Graben – An elongate trough or basin, bounded on both sides by high-angle *normal faults* that dip toward the interior of the trough.

Groundmass – The finer grained and/or glassy material between the *phenocrysts* in a *porphyritic* (see *porphyry*) igneous rock.

Hanging wall – The upper block of a non-vertical fault.

Hinge line – A line connecting the points of flexure or maximum curvature of the bedding planes in a *fold*.

Hornblende – The commonest mineral of the rock-forming amphibole group: $(Ca,Na)_{2\text{-}3}(Mg,Fe^{2+}, Fe^{3+},Al)_5(OH)_2[(Si,Al)_8O_{22}]$

Hydrostratigraphy – Division of a rock mass into hydrostratigraphic units; a hydrostratigraphic unit is a body of rock distinguished and characterized by its porosity and permeability. Hydrostratigraphy is the classification of rocks and sediment based on their capacity to transmit water, and rocks are typically designated as either aquifers or aquitards (Maxey, 1964; Hansen, 1991). Hydrostratigraphic units may (1) coincide with lithostratigraphic units, (2) have boundaries corresponding to facies changes within a single lithostratigraphic unit, or (3) encompass several lithostratigraphic units with similar water-transmitting properties (Maxey, 1964; Hansen, 1991).

Joint – A planar or nearly planar fracture in rock, along which negligible relative movement has occurred.

Lacustrine – Pertaining to, produced by, or formed in a lake.

Latite – A porphyritic extrusive rock having phenocrysts of plagioclase and potassium feldspar in nearly equal amounts, little or no quartz, and a finely crystalline to glassy groundmass; the extrusive equivalent of *monzonite*.

Lava flow – The solidified body of rock formed from a surficial outpouring of molten lava from a vent or fissure; also the outpouring itself.

Limestone – A sedimentary rock consisting chiefly of calcium carbonate, principally in the form of the mineral calcite; formed by either organic or inorganic processes, and may be detrital, chemical, oolitic, crystalline, or recrystallized; many are highly fossiliferous and represent ancient shell banks or coral reefs; rock types include micrite, calcarenite, coquina, chalk, and travertine.

Lithology – The description of rocks on the basis of such characteristics as color, mineralogic composition, and grain size.

Lithostratigraphic unit – A defined body of sedimentary, extrusive igneous, or metamorphosed sedimentary or volcanic strata that is distinguished and delimited on the basis of lithic characteristics and stratigraphic position. Boundaries of lithostratigraphic units are placed at positions of lithic change, either at distinct contacts or arbitrarily within zones of gradation. The fundamental unit is the formation.

Mica – A group of sheet-silicate minerals of general formula: $(K,Na,Ca)(Mg,Fe,Li,Al)_2(OH,F)_2[(Si,Al)_4O_{10}]$.

Microcrystalline – Said of a texture of a rock, consisting of crystals that are small enough to be visible only under the microscope.

Monzonite – A group of plutonic rocks containing approximately equal amounts of alkali feldspar and plagioclase, little or no quartz, and commonly augite as the main mafic mineral.

Mudstone – A fine-grained sedimentary rock in which the proportions of clay and silt are approximately equal.

Muscovite – A mineral of the mica group: $KAl_2(OH)_2[(AlSi_3)O_{10}]$.

Nepheline – A greasy gray hexagonal mineral of the *feldspathoid* group: $(Na,K)[AlSiO_4]$.

Normal fault – A fault along which the *hanging wall* has moved downward relative to the *footwall*.

Oligoclase – A mineral of the *feldspar* group: $KAlSi_3O_8$.

Olivine – An olive-green mineral common in magnesium-rich igneous rocks: $(Mg, Fe)_2SiO_4$.

Orthoquartzite – A clastic sedimentary rock that is made up almost exclusively of *quartz* sand, and that is relatively free of or lacks a fine-grained matrix.

Permeability – A coefficient describing the rate at which fluid can flow through a porous or fractured medium.

Phenocryst – A relatively large, conspicuous crystal in a *porphyritic* (see *porphyry*) igneous rock.

Phreatophyte – A type of plant that typically has a high rate of *transpiration* by virtue of a taproot extending to the water table.

Plagioclase – A group of the *feldspar* minerals, including albite, $Na[AlSi_3O_8]$, and anorthite, $Ca[Al_2Si_2O_8]$, which form a complete solution series at high temperatures.

Porphyry – An igneous rock of any composition that contains conspicuous *phenocrysts* in a fine-grained groundmass.

Potassium feldspar – An *alkali feldspar* of the composition $K[AlSi_3O_8]$, including orthoclase, microcline, and sanidine.

Pumice – A light-colored, vesicular, glassy volcanic rock commonly having the composition of *rhyolite*.

Pyroclast – An individual *pyroclastic* fragment.

Pyroclastic – Pertaining to clastic rock material formed by volcanic explosion or aerial expulsion from a volcanic vent.

Pyroxene – A group of dark-colored, rock-forming minerals with the general formula: $A_2B_2[Si_4O_{12}]$, where A = Ca, Na, Mg, or Fe^{2+}, and B = Mg, Fe^{2+}, Fe^{3+}, Cr, Mn, or Al.

Quartz – Crystalline silica, an important rock-forming mineral: SiO_2.

Quartz monzonite – An intrusive rock in which *quartz* comprises 10-50% of the *felsic* constituents, and in which the *alkali feldspar*/total *feldspar* ratio is between 35% and 65%.

Quartzite – A metamorphic rock consisting mainly of quartz and formed by recrystallization of *sandstone* or *chert*.

Reverse fault – A fault that dips greater than 30 degrees, along which the hanging wall has moved upward relative to the footwall.

Rhyolite – A group of light-colored volcanic rocks, typically *porphyritic* and exhibiting flow texture, containing *phenocrysts* of *quartz* and *alkali feldspar* in a glassy to *cryptocrystalline groundmass*.

Sandstone – A medium-grained clastic sedimentary rock composed of abundant rounded or angular fragments of sand size and more or less firmly united by a cementing material.

Scoria – A *bomb*-sized *pyroclast* that is irregular in form and generally very vesicular.

Shale – A laminated, indurated rock with >67% clay-sized minerals.

Silica – The chemically resistant dioxide of silicon: SiO_2. It occurs naturally in several crystalline polymorphs (for example, the minerals quartz, tridymite, cristobalite, coesite, and stishovite); in *cryptocrystalline* form (chalcedony); in amorphous and hydrated forms (opal); and combined in silicates as an essential constituent of many minerals.

Silicic – Said of a *silica*-rich igneous rock or magma.

Sill – A tabular igneous intrusion that parallels the bedding or *foliation* of the sedimentary or metamorphic country rock, respectively.

Siltstone – An indurated silt having the texture and composition of *shale* but lacking its fine lamination or fissility.

Sodium feldspar – An alkali feldspar containing the albite molecule ($Na[AlSi_3O_8]$).

Specific capacity – An expression of the productivity of a well, obtained by dividing the rate of discharge of water from the well by the drawdown of the water level in the well.

Specific capacity test – An aquifer test in which water levels in only the pumping well are measured.

Stock – A relatively small, concordant and/or discordant plutonic body having an aerial extent less than 40 square miles (100 km^2) and no known floor.

Stratigraphy – The science of rock strata, concerned with the original succession and age relations of rock strata and with their form, distribution, lithologic composition, fossil content, and geophysical and geochemical properties.

Strike – The angle a planar feature makes relative to north, as measured in a horizontal plane.

Syncline – A *fold*, the core of which contains stratigraphically younger rocks, and is convex downward.

Tephra – A collective term used for all *pyroclastic* material ejected during an explosive volcanic eruption.

Thrust fault – A *fault* that dips 30 degrees or less, along which the hanging wall has moved upward relative to the footwall.

Transmissivity – The rate at which a fluid is transmitted through a unit width of an aquifer under a hydraulic gradient.

Transpiration – The process by which plants give off water vapor through their leaves.

Unconformity – A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession.

Vesicular – Said of the texture of a lava rock characterized by abundant vesicles (cavities of variable shape, formed by the entrapment of a gas bubble during solidification of the lava).

Vitrophyre – Any porphyritic igneous rock having a glassy groundmass.

Welded tuff – A glass-rich pyroclastic rock that has been indurated by the welding together of its glass shards under the combined action of the heat retained by particles, the weight of overlying material, and hot gases. It is generally composed of silicic pyroclastics and appears banded or streaky.

APPENDICES

APPENDIX A

Explanatory material for Plate 1.

DESCRIPTION OF GEOLOGIC MAP UNITS

The following geologic unit descriptions are generalized from more detailed work in the following sources: surficial units – Hurlow (unpublished mapping and field observations), Larsen (1960), and Davis (1983); Tertiary rocks – Bullock (1951), Morris (1964a, 1964b), and Waite and others (1997); bedrock units – Bullock (1951), Bissell (1959), Rigby and Clark (1962), Morris (1964a, 1964b), and Moore (1973a, 1973b).

Quaternary

Alluvial Deposits

Qay **Younger alluvium (Holocene) –** Moderately to well-sorted, moderately to well-layered, interbedded gravel, sand, silt, and clay; includes channel, flood-plain, terrace, and local small alluvial-fan and colluvial deposits. Found in stream channels throughout the study area but relatively few are large enough to show on plate 1. Up to about 10 feet (3 m) thick.

Qac **Alluvium and colluvium (Holocene) –** Poorly to well-sorted sand, gravel, silt, and clay deposited in stream-channel, alluvial-fan, and hillslope environments. Mapped where alluvial and colluvial deposits are gradational and/or too small to differentiate. Up to about 30 feet (10 m) thick.

Qafy **Alluvial-fan deposits (Holocene and Pleistocene) –** Poorly sorted, structureless to moderately layered gravel, sand, silt, and clay; clasts are pebble- to boulder-size; deposited along valley margins in debris-flow and alluvial environments. Qafy deposits were deposited after, and possibly during the late stages of, Lake Bonneville. Up to about 150 feet (45 m) thick.

Qafo **Older alluvial-fan deposits (Pleistocene; pre-Lake Bonneville) –** Poorly sorted, structureless to moderately layered gravel, sand, silt, and clay; clasts are pebble- to boulder-size; deposited along valley margins in debris-flow and alluvial environments where streams and ephemeral drainages enter the valley. These alluvial fans show a greater degree of weathering and modification than Qafy deposits. They form a major component of the basin-fill deposits along the valley margins. Up to about 1,500? feet (460? m) thick.

Qao **Older alluvium (Pleistocene) –** Undivided stream alluvium and alluvial-fan deposits. Stream deposits are moderately to well-sorted, moderately to well-layered, interbedded gravel, sand, silt, and clay, and alluvial-fan deposits are poorly sorted, structureless to moderately layered gravel, sand, silt, and clay with pebble- to boulder-size clasts. Up to about 30 feet (10 m) thick.

Lacustrine Deposits

Qlf **Lacustrine fine-grained deposits –** Pale tan, structureless to laminated clay and silty clay deposited by Lake Bonneville. Up to about 1,000? feet (300? m) thick.

Qlsg **Lacustrine sand and gravel –** Well-sorted, medium- to fine-grained sand or well-sorted pebble gravel forming linear bars near erosional shoreline features. Deposited as shoreline or offshore gravel or sand bars. About 10 to 30 feet (3-10 m) thick.

Qlf/Qafo **Lacustrine fine-grained deposits overlying older alluvial-fan deposits** -- Mapped where surficial deposits are lakebed clay and silt, but topography indicates an alluvial fan.

Qlf/Qafo/Tsl Lacustrine fine-grained deposits overlying older alluvial-fan deposits overlying Salt Lake Formation -- Mapped in the Mosida Hills where lacustrine clay and older alluvial-fan deposits form a thin mantle over the Salt Lake Formation.

Other Surficial Deposits

Qes **Eolian sand –** Pale gray, fine-grained, well-sorted dune sand and silt. Some dunes in the valley center are active, but most are stable. These deposits represent wind-reworked lacustrine sand and silt. About 3 to 10 feet (1-3 m) thick.

Qg **Glacial deposits –** Poorly sorted, structureless gravel, sand, silt, and clay deposited as moraines during glacial epochs, presumably the last glacial maximum about 30 to 12 ka. Thickness unknown.

unconformity

Quaternary-Tertiary

QTu **Quaternary and Tertiary basin-fill deposits, undivided** – Shown only on cross sections (plate 2).

QTs **Alluvium and colluvium** – Poorly to moderately sorted, structureless to moderately layered sand, silt, and limestone-clast gravel forming isolated mantles on Tertiary volcanic rocks. Up to about 30 feet (10 m) thick.

QTp **Pediment deposits** – Veneer of alluvium capping a pediment surface cut on Salt Lake Formation in Rush Valley; 5 to 30 feet (2-10 m) thick.

unconformity

Tertiary

Tb **Basalt** – Flow rock with dark gray to black, dense, sparsely vesicular groundmass, and fine-grained, subhedral olivine and/or plagioclase phenocrysts. Up to about 30 feet (10 m) thick.

unconformity

Tsl **Salt Lake Formation** – Claystone and minor sandstone, conglomerate, and limestone. The claystone is variegated purple, red-brown, black, and gray, and well laminated. The sandstone and conglomerate are locally interbedded and locally gradational, pale tan to pale gray, poorly to moderately sorted, and poorly bedded, with pebble-size clasts of Paleozoic limestone and volcanic rocks. The limestone is pale gray to white, with poorly to moderately defined bedding, unfossiliferous, and is about 5 to 15 feet (2-5 m) thick. Total thickness 0 to 400+ feet (0-120+ m).

unconformity

Tio **Intrusive rocks - Oligocene** – This unit includes intrusions in the East Tintic Mountains and in the southwestern Oquirrh Mountains. Intrusive rocks in the East Tintic Mountains include monzonite porphyry dikes, stocks, and intrusive breccia that intrude overlying and genetically related volcanic deposits. Most bodies are too small to show on plate 1. Rock types include quartz monzonite porphyry, monzonite porphyry, biotite monzonite porphyry, and hornblende monzonite porphyry. The Silver City stock, the largest intrusive body in the Tintic Mountains, yielded a K-Ar radiometric age of 31.5 ± 0.9 Ma on biotite (Laughlin and others, 1969). These intrusions are associated with mineralization in the East Tintic district (Morris and Lovering, 1979). Oligocene intrusions in the southwestern Oquirrh Mountains consist of rhyolite porphyry sills, dikes, domes, and stocks that yielded K-Ar ages on biotite of 31.6 ± 0.9 Ma (Moore, 1973a) to 36.7 ± 0.5 Ma (Moore and McKee, 1983). These intrusions are associated with mineralization in the Mercur district (Kerr, 1997).

intrusive contact

Tvo **Volcanic rocks - Oligocene** – This unit includes thick accumulations of volcanic deposits in two main areas: the East Tintic Mountains in the southern part of the study area and the eastern Traverse Mountains in the northern part of the study area. Smaller, scattered outcrops are also present in the Mosida Hills. Rock types in the East Tintic Mountains include latite flow rocks, welded tuffs, vitrophyre, conglomerate, non-welded tuffs, and related intrusions of the Laguna Springs and Tintic Mountain volcanic groups, and the Packard quartz latite (Morris, 1964a, 1964b; Morris and Lovering, 1979), undivided on plate 1. K-Ar radiometric ages on biotite from flow rocks range from 32.8 ± 1.0 Ma (Laughlin and others, 1969) to 32.2 ± 1.0 Ma (Morris and Lovering, 1979). Volcanic rocks in the eastern Traverse Mountains include rhyolite to latite lava flows, ash-flow tuffs, and breccias (Waite and others, 1997). Radiometric ages range from 30.7 ± 0.9 Ma (K-Ar on biotite [Moore, 1973a]) to 32.12 ± 0.14 Ma ($^{40}Ar/^{39}Ar$ on plagioclase [Deino and Keith, 1997]). Up to about 5,200 feet (1,580 m) thick.

unconformity

Tve **Volcanic rocks - Eocene** -- Debris flows, ash-flow tuffs, flow breccias, and nepheline basalt that form a large volcanic field in the western Traverse Mountains (Waite and others, 1997). Flow rocks from this unit yielded $^{40}Ar/^{39}Ar$ radiometric ages ranging from 37.82 ± 0.14 Ma on whole rock to 39.18 ± 0.11 Ma on biotite (Deino and Keith, 1997). About 1,400 feet (425 m) thick.

unconformity

Tc **Conglomerate** – Medium- to coarse-grained, poorly to moderately well-bedded, moderately to poorly sorted conglomerate; 0 to over 500 feet (0-150+ m) thick. This unit includes two small, widely separated outcrop areas, possibly of different age and depositional origin. In the East Tintic Mountains, Tc underlies Oligocene volcanic rocks and is Eocene(?) in age; at Fivemile Pass and in the southern Traverse Mountains, it forms isolated patches overlying the Great Blue Limestone and has no other age constraints. Up to about 500 feet (150 m) thick.

unconformity

Pennsylvanian

IPo **Oquirrh Group, undivided** – Shown only on the southern half of the Lake Mountains, where the source map for plate 1 (Davis, 1983) did not subdivide the Group into formations. Includes the lower member of the Butterfield Peaks Formation and the West Canyon Limestone in the Lake Mountains, where it is up to about 4,000 feet (1,220 m) thick.

IPbmm **Markham Member of the Bingham Mine Formation** – Orthoquartzite, calcareous sandstone, and rare thin cherty limestone; about 3,700 feet (1,130 m) is exposed only in the northeastern corner of the map area.

IPbmc **Clipper Member of the Bingham Mine Formation** – Orthoquartzite, calcareous sandstone, and minor shale and cherty limestone; about 8,200 feet (2,500 m) thick; exposed only in the northeastern corner of the map area.

IPbpu **Upper unit of the Butterfield Peaks Formation** – Tan-weathering quartzite, light-gray, platy calcareous sandstone, and minor dark gray shale; about 770 feet (235 m) exposed only in the northern part of the map.

IPbpl **Lower unit of the Butterfield Peaks Formation** – Interbedded orthoquartzite, sandstone, and limestone, and minor mudstone and bedded chert. The orthoquartzite and sandstone are pale gray to brown, fine grained, well sorted, and planar to cross-bedded, in beds 3 to 30 feet (1-10 m) thick. The limestone ranges from pale gray to dark blue-gray and is medium to fine grained, and contains variable amounts of silt, chert, and fossil fragments; structureless to well bedded in beds 3 to 30 feet (1-10 m) thick. The mudstone is poorly exposed, pale to dark gray or purplish to reddish gray, and weakly laminated to structureless. Up to about 4,500 feet (1,370 m) thick.

Pennsylvanian-Mississippian

IPMwc **West Canyon Limestone** – Pale gray to dark bluish gray, medium to fine grained limestone, and variable amounts of silt, chert, and fossil fragments; structureless to well bedded in beds 3 to 30 feet (1-10 m) thick. Up to about 1,860 feet (570 m) thick.

IPMmc **Manning Canyon Shale** – Shale and relatively minor interbedded orthoquartzite and limestone. The shale is black to medium gray, variably sandy, silty, clayey, and/or calcareous, and soft to fissile. The orthoquartzite is medium gray to rust-brown weathering, medium to fine grained, having thin planar lamination or cross-bedding, in beds about 1 to 6 feet (0.3-2 m) thick. The limestone is medium to dark gray, fine grained, structureless to moderately well bedded, and variably fossiliferous. The total thickness of the Manning Canyon Shale varies from about 1,200 feet (365 m) in the eastern part of the study area to 1,560 feet (475 m) in the west.

Mississippian

Mgb **Great Blue Limestone, undivided** – Shown only adjacent to the Lake Mountains, where the source map for plate 1 (Davis, 1983) did not subdivide the formation into members. About 2,530 feet (770 m) thick.

Mgbu **Upper member of the Great Blue Limestone** – Pale to medium gray, platy to thin-bedded, variably silty limestone; up to about 2,100 feet (640 m) thick.

Mgbm **Middle member of the Great Blue Limestone** – Black to medium gray calcareous shale with interbedded orthoquartzite and limestone. Also known as the Long Trail Shale Member. Up to about 850 feet (260 m) thick; about 90 feet (27 m) thick in the Lake Mountains (Biek, 2002b).

Mgbl **Lower member of the Great Blue Limestone** – Pale to dark gray, fine- to medium-grained, medium-bedded to structureless, medium- to thick-bedded, variably fossiliferous limestone. Up to about 1,080 feet (330 m) thick; about 300 feet (90 m) thick in the Lake Mountains (Biek, 2002b).

Mh **Humbug Formation** – Interbedded orthoquartzite, limestone, and minor dolomite. The orthoquartzite is pale tan to gray, fine grained, well sorted, planar to cross-bedded, in beds about 3 to 6 feet (1-2 m) thick. The limestone is medium to dark gray, fine to medium grained, well bedded to structureless in beds about 3 to 9 feet (1-3 m) thick, variably fossiliferous, and variably sandy and cherty. The dolomite is pale gray, fine grained to microcrystalline, hard, and structureless, in beds 1 to 3 feet (0.3-1 m) thick. The thickness of the Humbug Formation varies from about 650 feet (200 m) in the western part of the study area to about 1,030 feet (315 m) in the eastern part; about 700 to 750 feet (210-230 m) thick in the Lake Mountains (Biek, 2002b).

Md **Deseret Limestone** – Medium gray, fine- to medium-grained, well-bedded, variably fossiliferous cherty limestone. The chert is brown weathering, and forms thin, irregular, discontinuous beds. About 700 to 945 feet (215-290 m) thick.

Mg **Gardison Limestone** – Medium to dark gray, fine- to coarse-grained, moderately well-bedded to structureless, variably cherty limestone and dolomite, about 450 to 680 feet (135-205 m) thick.

Mf **Fitchville Formation** – The lower part of the Fitchville Formation consists of medium gray, fine-grained, well-bedded silty limestone, and the upper part consists of medium to fine-grained, medium to dark gray to black, variably fossiliferous, well-bedded, cherty dolomite. About 275 to 535 feet (85-165 m) thick.

Mississippian-Devonian

MDpv **Pinyon Peak Limestone and Victoria Formation, undivided** – The Pinyon Peak Limestone consists of blue-gray to medium gray, fine to medium-grained, well-bedded, variably fossiliferous limestone. The Victoria Formation is composed of tan to brown, medium-grained orthoquartzite and pale gray, fine-grained dolomite. The total thickness of this unit is 450 feet (135 m).

unconformity

Devonian-Ordovician

DSOu **Devonian-Ordovician limestone and dolomite, undivided** – This unit includes the Bluebell Dolomite, Fish Haven Limestone, and Opohonga Formation. The Bluebell Dolomite is medium- to dark-gray, fine to medium-grained, medium-bedded dolomite, and interbedded algal-laminated, cherty dolomite. The Fish Haven Limestone includes medium- to dark gray, medium-grained, structureless to moderately well-bedded, fossiliferous dolomite and limestone. The Opohonga Limestone is tan and medium gray, wavy-bedded, silty limestone. The total thickness of this unit is about 1,700 feet (520 m).

Cambrian

Ꞓu **Cambrian limestone and dolomite, undivided** – This unit includes the Ajax Dolomite, Opex Formation, Cole Canyon Dolomite, Bluebird Dolomite, Herkimer Limestone, Dagmar Dolomite, and Teutonic Limestone. These units are composed of dark and light gray, medium- to fine-grained, well to moderately bedded, variably fossiliferous, and variably mottled dolomite and limestone. The total thickness of this unit is about 2,750 feet (840 m).

Ꞓo **Ophir Formation** – Gray-green, sandy, fissile shale, with thin, blue-gray, silty limestone beds in the middle part; about 430 feet (130 m) thick.

Ꞓt **Tintic Quartzite** – White, tan, or brown, medium-grained, well-sorted, cross-bedded to structureless orthoquartzite; about 2,300 to 3,200 feet (700-975 m) thick.

unconformity

Middle Proterozoic

Yb **Big Cottonwood Formation** – Olive-green, tan, or brown orthoquartzite and shale; about 1,675 feet (510 m) exposed in the southernmost part of the study area.

Table A.1. *Source references for geologic map units shown on plate 1.*

This Report Map Symbol	**This Report** Unit Name	**Oquirrh Mountains** (Laes and others, 1997)	**Southern Wasatch Front** (Davis, 1983)	**Allens Ranch** (Proctor and others, 1959; Proctor, 1985)	**Fivemile Pass** (Bissell and Proctor, 1959)	**Boulter Peak** (Disbrow, 1961)	**Eureka** (Morris, 1964a)	**Tnitic Junction** (Morris, 1964b)	**Cedar Valley Hills** (Calderwood, 1951)	**Rush Valley** (Everitt and Kaliser, 1980)
Qay	Younger alluvium	Qa	Qa	Qal	Qal	Qs	Qya	Qya	-	Qya
Qao	Older alluvium	Qa	Qa	Qal	Qal	Qs	Qoa	Qoa	-	QToa
Qes	Eolian sand	-	Qac	Qlb	-	-	-	-	-	-
Qac	Alluvium and colluvium	Qa	Qa	Qal	Qal	Qs	Qoa	Qoa	-	-
Qafy	Younger alluvial-fan deposits	Qa	Qa, Qfg	Qal	Qal	Qs	Qoa	Qoa	-	Qya
Qafo	Older alluvial-fan deposits	Qa	Qfg	Qal	Qal	Qs	Qoa	Qoa	-	QToa
Qlf	Fine-grained lakebed deposits (silt and clay)	Qa	Qlb, Qac	Qlb	Qal	Qs	Qba	Qoa	-	Qbs
Qlf/Qafo	Fine-grained lakebed deposits overlying older alluvial-fan deposits	Qa	Qlb, Qfg	Qlb	Qal	Qs	Qba	Qoa	-	-
Qlf/Qafo/Tsl	Fine-grained lakebed deposits overlying older alluvial-fan deposits and Salt Lake Formation	-	Qlb, Tsl	Qlb	-	-	-	-	-	-

Table A.1. *(continued)*

Qlsg	Lacustrine shoreface deposits (sand and gravel)	Qa	Qpsf, Qba	Qlb	Qal	Qs	Qba	Qba	-	Qbg
Qg	Glacial deposits	Qg	-	-	-	-	-	-	-	-
QTp	Pediment deposits	-	-	-	-	-	-	-	-	QTp
QTs	Alluvium and colluvium	-	-	-	-	-	-	-	-	-
Tb	Basalt	-	Tv	Tb	-	-	-	-	-	-
Tsl	Salt Lake Formation	-	Tsl	-	-	-	Tsl	Tsl	-	-
Tio	Oligocene intrusive Rocks	Tr, Tm	-	-	-	-	Tqm, Tsc, Tbm, Tsp, Thm	Td, Tlp	-	-
Tvo	Oligocene volcanic rocks	Tlf, Tlah, Tlb, Trf, Tnb	Tv	Tlss, Tlsb, Tlsa, Tlsl, Tptb, Tpr	Tla, Trbx, Ttbx	Tlsf, Tlst	Tlg, Tlf, Tlt, Ts, Tp	Ts, Tp	-	-
Tie	Eocene intrusive rocks	Tm, Tr	-	-	-	-	-	-	-	-
Tve	Eocene volcanic rocks	Tlf, Tlah	-	-	-	-	-	-	-	-
Tc	Conglomerate	Tc	-	TQ	-	Tcg	-	Ta	-	-
IPo	Oquirrh Group, undivided	-	-	-	-	-	-	-	-	-
IPbmm	Markham Member of Bingham Mine Formation	IPbmm	-	-	-	-	-	-	-	-
IPbmc	Clipper Member of Bingham Mine Formation	IPbmc	-	-	-	-	-	-	-	-
IPbpu	Upper Member of Butterfield Peaks Formation	IPbpu	-	-	-	-	-	-	-	-

Table A.1. *(continued)*

IPbpl	Lower Member of Butterfield Peaks Formation	IPbpl	PIPo	-	IPlp, IPcf	IPo_2	-	-	-	-
IPMwc	West Canyon Limestone	IPwc	PIPo	PIPo	IPmd, IPhc	IPo_1	-	-	-	-
IPMmc	Manning Canyon Shale	IPMmc	IPMmc	Pmc, Mmc	Mmcl, IPmcm, IPmcu	IPMmc	-	-	-	-
Mgbu	Upper member of Great Blue Limestone	Mgbus, Mgbu	Mgb	Mgbk	Mgb_4	Mgb_3	Mgp	Mgb	Mgb	-
Mgb	Great Blue Limestone, undivided	-	Mgb	-	-	-	-	-	Mgb	-
Mgbm	Middle member of Great Blue Limestone	Mgblt	Mgb	Mgbc	Mgb_3	Mgb_2	Mgc	Mgb	Mgb	-
Mgbl	Lower member of Great Blue Limestone	Mgbm, Mgbl	Mgb	Mgbp, Mgbt	Mgb_1, Mgb_2	Mgb_1	Mgt	Mgb	Mgb	-
Mgb	Great Blue Limestone, undivided	-	Mgb	-	-	-	-	-	Mgb	-
Mh	Humbug Formation	Mh	Mh	Mh	Mh	Mh	Mh	Mh	Mh	-
Md	Deseret Limestone	Md	Md	Md	Mpcu, Mpcl	Md	Md	Md	Mpc	-
Mg	Gardison Limestone	Mg	-	Mg	Mpcl, Mgu	Mg	Mg	Mg	-	-
Mf	Fitchville Formation	-	-	Mf	Mgl	Mf	Mf	Mf	Mg	-

Table A.1. *(continued)*

MDpv	Pinyon Peak Limestone and Victoria Formation	-	-	DMpp, Dv	Dpp, Dv	MDpv	MDpv	MDpv	Dpp	-
DSOu	Devonian-Ordovician limestone and dolomite, undivided	-	-	SDb, Ofh , Oo	Sbl, Obl, Oop	DSOb,Of, Oop	DSOb,Of, Oo	DSOb,Of, Oop	-	-
ɭ u	Cambrian limestone and dolomite, undivided	ɭ bb, ɭ h	-	ɭ au, ɭ am, ɭ al, ɭ o, ɭ cc	ɭ aj	ɭ aj, ɭ op, ɭ cc, ɭ b, ɭ h, ɭ d, ɭ te	ɭ a, ɭ op, ɭ cc, ɭ b, ɭ h, ɭ d, ɭ te	ɭ a, ɭ op, ɭ cc, ɭ b, ɭ h, ɭ d, ɭ te	-	-
ɭ o	Ophir Formation	ɭ op	-	-	-	ɭ o	ɭ o	ɭ o	-	-
ɭ t	Tintic Quartzite	-	-	-	-	ɭ t	ɭ t	ɭ t, ɭ tf	-	-
Yb	Big Cottonwood Formation	-	-	-	-	-	-	pɭ b	-	-

- Unit is not present on source map in area used for this compilation.

Explanation of map symbols in source publications:

Oquirrh Mountains (Laes and others, 1997) – Qa, alluvium; Tr, rhyolitic intrusions; Tm, monzonite; Tlb, latitic breccia; Trf, rhyolitic flow; Tlf, latite flow; Tlb, tuff breccia; Tlah, latite lahar; Tnb, nepheline basalt; Mgbus, upper shale member of Great Blue Limestone; Mgbm, Mercur Series of Great Blue Limestone; ɭ bb, Bluebird Dolomite; ɭ h, Herkimer Limestone; ɭ op, Ophir and Pioche Formations.

Table A.1. *(continued)*

Southern Wasatch Front (Davis, 1983) – Qa, alluvial deposits; Qlb, Provo Formation and younger lake bottom sediments; Qpsf, Provo Formation and younger shore facies; Qba, Bonneville and Alpine Formations; Qac, Alpine Formation; Qfg, fanglomerate.

Allens Ranch quadrangle (Proctor and others, 1959; Proctor, 1985) – Tlss, Sable Valley limestone; Tlsb, Laguna Springs boulder conglomerate; Tlsa, Laguna Springs agglomerate; Tlsl, Laguna Springs latite; Tptb, Packard rhyolite breccia; Tpr, Pakard rhyolite welded tuff; Tc, limestone colluvium; SDb, Bluebell dolomite; Ofh, Fish Haven Dolomite; Oo, Opohanga [sic] Limestone; ɭ au, upper member of Ajax Limestone; ɭ ac, cherty member of Ajax Limestone; ɭ al, lower member of Ajax Limestone; ɭ o, Opex Limestone; ɭ cc, Cole Canyon Formation.

Fivemile Pass quadrangle (Bissell and Proctor, 1959) – Qal, unconsolidated deposits; Tla, latite; Trbx, rhyolite breccia; Ttbx, tuff breccia; Mgb_4, upper limestone member of Great Blue Formation; Mgb_3, Long Trail Shale Member of Great Blue Formation; Mgb_2, middle limestone member of Great Blue Formation; Mgb_1, lower limestone member of Great Blue Formation; Mpcu, upper member of Pine Canyon Limestone; Mpcl, lower member of Pine Canyon Limestone; Mgu, upper member of Gardner Formation; Mgl, lower member of Gardner Formation; Dpp, Pinyon Peak Limestone; Dv, Victoria Formation; Sbl, Bluebell Dolomite; Obl, Bluebell Dolomite; Oop, Opohonga Limestone; ɭ aj, Ajax Limestone.

Boulter Peak quadrangle (Disbrow, 1961) – Qs, unconsolidated sediments; Tlsf, Laguna Springs latite flows; Tlst, Laguna Springs latite tuff; Tcg, conglomerate; Mgb_3, upper member of Great Blue Formation; Mgb_2, middle member of Great Blue Formation; Mgb_1, lower member of Great Blue Formation; DSOb Bluebell dolomite; Of,

Table A.1. *(continued)*

Fish Haven dolomite; Oop, Opohonga Limestone; ⌊ aj, Ajax Dolomite; ⌊ op, Opex Formation; ⌊ cc, Cole Canyon Dolomite; ⌊ b, Bluebird Dolomite; ⌊ h, Herkimer Limestone; ⌊ d, Dagmar Dolomite; ⌊ te, Teutonic Limestone; ⌊ o, Ophir Formation; ⌊ t, Tintic Quartzite.

Eureka (Morris, 1964a) – Qba, Bonneville Formation and Alpine Formation; Tqm, quartz monzonite porphyry; Tsc, monzonite of the Silver City stock; Tbm, associated biotite monzonite porphyry of the Silver City stock; Tsp, monzonite porphyry of the Sunrise Peak stock; Thm, hornblende monzonite porphyry; Tlg, interlayered conglomerate, flows, agglomerate, and tuff of the Laguna Springs latite; Tlf, latite and andesite flow rocks of the Laguna Springs latite; Ts, Swansea quartz monzonite; Tp, Packard quartz latite; Mgp, Poker Knoll Limestone Member of Great Blue Formation; Mgc, Chiulos Member of Great Blue Formation; Mgt, Paymaster and Topliff Members of Great Blue Formation; DSOb Bluebell Dolomite; Ofh, Fish Haven Dolomite; Oo, Opohonga Limestone; ⌊ aj, Ajax Dolomite; ⌊ op, Opex Formation; ⌊ cc, Cole Canyon Dolomite; ⌊ b, Bluebird Dolomite; ⌊ h, Herkimer Limestone; ⌊ d, Dagmar Dolomite; ⌊ te, Teutonic Limestone; ⌊ o, Ophir Formation; ⌊ t, Tintic Quartzite.

Tintic Junction (Morris, 1964b) - Tsc, monzonite of the Silver City stock; Ts, Swansea quartz monzonite; Tp, Packard quartz latite; Ta, Apex conglomerate; DSOb, Bluebell Dolomite; Ofh, Fish Haven Dolomite; Oo, Opohonga Limestone; ⌊ aj, Ajax Dolomite; ⌊ op, Opex Formation; ⌊ cc, Cole Canyon Dolomite; ⌊ b, Bluebird Dolomite; ⌊ h, Herkimer Limestone; ⌊ d, Dagmar Dolomite; ⌊ te, Teutonic Limestone; ⌊ o, Ophir Formation; ⌊ t, Tintic Quartzite.

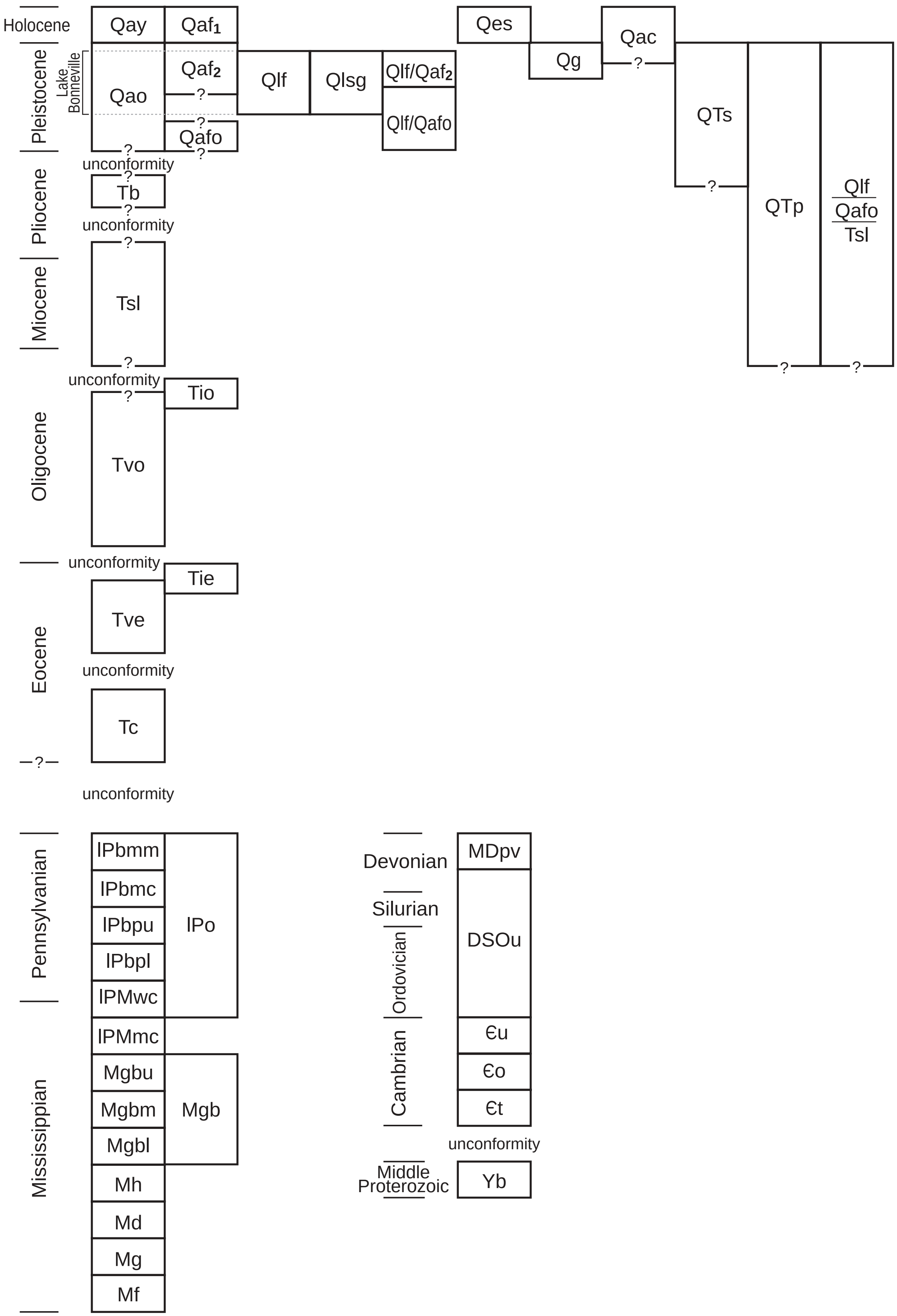

Figure A.1. *Correlation of stratigraphic units. No vertical scale implied.*

APPENDIX B

Ground-water chemistry data and analysis.

Table B.1. *Chemical analyses of water from wells and springs in Cedar Valley.*

ID[1]	Sampling Site Location[2]	Date of collection	Temperature °C	Silica SiO_2 (ppm)	Calcium Ca (ppm)	Magnesium Mg (ppm)	Sodium plus Potassium Na + K (ppm)	Bicarbonate HCO_3 (ppm)	Carbonate CO_3 (ppm)	Sulfate SO_4 (ppm)	Chloride Cl (ppm)	Nitrate NO_3 (ppm)	Dissolved solids[3] (ppm)	Hardness as $CaCO_3$ (ppm)	Noncarbonate Hardness as $CaCO_3$ (ppm)	Sodium adsorption ratio (SAR)	Specific Conductance (micromhos/ cm at 25 °C)	pH
SPRINGS																		
From basin fill																		
S11	(C-6-2)29ccc-1	9/9/1965	52	11	57	18	9.2	232	0	18	17	1.4	262	214	24	0.3	444	7.7
From bedrock																		
S1	(C-4-2)26cbc	4/7/1966	nd	48	77	10	41	220	0	33	76	0.8	431	234	54	1.2	634	7.7
S2	(C-4-3)20dba	11/3/1965	45	7	95	13	10	330	0	25	11	0.3	323	290	19	0.3	558	7.6
S3	(C-4-3)26cbd	11/3/1965	51	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	771	nd
S4	(C-4-3)26dda	11/3/1965	49	12	130	28	47	447	0	58	80	0.1	558	438	71	1	1,000	7.7
S5	(C-4-3)27bab	11/3/1965	48	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	670	nd
S6	(C-5-1)17bdc	8/25/1965	nd	49	148	30	57	148	12	56	295	2.1	853	494	353	1.1	1,360	8.5
S7	(C-5-3)4cdc	11/2/1965	45	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	477	nd
S8	(C-5-3)4dcd	11/2/1965	42	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	518	nd
S9	(C-5-3)36cba	7/22/1965	46	6.5	62	16	2.9	240	0	15	8	3.5	227	220	23	0.1	424	7.6
S10	(C-6-2)6cad	7/22/1965	50	8	88	12	5.5	288	0	27	11	2.1	290	269	33	0.1	520	7.7
S12	(C-6-3)1aad	7/22/1965	47	6.8	65	16	4	248	0	17	8.7	3.2	235	227	24	0.1	436	8.2
S13	(C-6-3)15bad	6/21/1965	52	6.9	67	29	12	303	0	38	20	0.2	321	289	41	0.3	586	7.7
WELLS																		
In basin fill																		
4	(C-6-2)26cbb-1	7/1/1965	53	53	36	30	20	246	0	27	19	0.2	298	212	10	0.6	470	8.2
18	(C-5-2)26bbb-1	6/30/1965	53	19	80	14	21	262	0	37	34	1.1	337	257	42	0.6	572	7.6
87	(C-6-2)29ccc	6/3/1965	nd	10	59	20	8.7	236	0	29	18	2.3	253	232	38	0.3	457	8.1
134	(C-6-2)14cac-1	6/8/1965	59	53	31	14	20	170	0	14	16	1	229	134	0	0.7	344	8
1029	(C-6-2)13caa-1	7/1/1965	61	55	35	18	37	208	0	38	21	0.4	300	160	0	1.3	461	8
1031	(C-6-2)14cba-1	6/8/1965	59	48	27	13	26	174	0	14	14	0.2	225	120	0	1	346	7.6
1037	(C-6-2)29bdd-1	7/30/1965	51	11	58	17	5.9	228	0	17	15	2.7	235	215	28	0.2	430	7.6
1039	(C-6-2)32bbd-1	6/30/1965	nd	14	56	27	12	248	0	40	21	1	290	250	47	0.3	507	8.1
1054	(C-7-2)35bcc-1	3/29/1966	nd	23	42	114	383	487	0	842	94	0.4	1,740[5]	575	176	7	2,430	7.8
1118	(C-6-2)14dba-1	6/9/1965	64	46	29	13	36	198	0	22	14	0	253	126	0	1.4	393	8.1
1120	(C-6-2)15bbb-1	6/8/1965	53	40	80	32	14	263	0	36	78	0.7	451	332	116	0.3	709	7.7
1121	(C-6-2)15cbb-1	6/8/1965	53	40	46	20	8.6	194	6	23	17	2.1	273	200	41	0.3	434	8.4
1123	(C-6-2)15bcb-1	6/8/1995	53	38	55	26	16	248	0	37	26	0	313	244	41	0.4	512	8.1
1127	(C-8-2)15aad-1	Mar-66	nd	52	30	92	439	764	0	638	84	0.5	1,710[5]	455	0	8.9	2,410	8.1
1128	(C-7-2)25bdb-1[6]	3/31/1966	54	32	28	135	480	518	0	941	140	0.4	2,020[5]	625	200	7.4	2,870	8.1
1129	(C-8-2)18bcb-1	Mar-66	nd	10	31	24	75	226	0	72	56	1.5	391	176	0	2.5	668	7.8
1130	(C-8-2)31adb-1	Mar-66	nd	38	26	19	101	228	0	64	79	0.5	448	146	0	3.6	717	7.7
1131	(C-6-2)32cbc-1	10/4/1965	nd	19	67	30	31	325	0	49	29	0.1	380	292	26	0.8	647	7.9
1132	(C-6-2)33bcb-1	1/3/1966	nd	15	32	16	33	193	0	34	16	0.3	237	146	0	1.2	424	8
In bedrock																		
56	(C-6-1)18dca-1	7/1/1965	81	21	75	25	35	240	0	70	66	1.4	421	288	91	0.9	706	7.7
1023	(C-6-1)31dab-1[4]	7/1/1965	61	46	82	116	179	324	0	291	355	0.7	1,230[5]	680	414	3	2,060	7.8
156[7]	N 250 E 200 SW 16 5S 1W	4/26/1999	nd	nd	3,600	70	282	nd	nd	233	293	0.6	1,060	nd	nd	nd	1,790	7.6
1011[7]	N 100 E 1,420 SW 14 5S 2W	4/6/1999	nd	nd	190	27	34	nd	nd	24	69	1.2	488	nd	nd	nd	578	7.6
1125[7]	N 25 E 3,100 SW 17 5S 1W	4/16/1999	nd	nd	73	26	166	nd	nd	150	166	0.4	684	nd	nd	nd	1,280	7.8
1126[7]	S 1,900 W 2,600 NE 30 5S 1W	8/18/1999	nd	nd	370	62	45	nd	nd	71	146	1.7	588	nd	nd	nd	877	7.6
1018[8]	N 1,012 W 200 S4 18 6S 1W	7/31/1994	nd	nd	70	28	45	nd	nd	70	63	nd	422	nd	nd	nd	nd	nd

Notes
1. Data are from Feltis (1967, table 4, p. 27) except where noted.
2. Locations given in U.S. Geological Survey or Point of Diversion notation - see figures C.1 or C.2, respectively, for explanation.
3. Residue on evaporation at 180° C unless indicated otherwise.
4. Analysis includes 2.2 ppm fluoride.
5. Calculated from determined constituents.
6. Analysis includes 0.00 ppm iron (at time of analysis), 4.0 ppm fluoride, and 1.3 ppm boron.
7. Eagle Mountain City test well. Data supplied by T. Jarvis of Montgomery Watson Harza, Inc. (written communication, 2001) with permission of Eagle Mountain City.
8. Screened in both bedrock and basin-fill aquifers; main production is from bedrock (Montgomery, 1995).

nd - no data

Table B.2. *Ratios of selected species concentrations to total dissolved solids (TDS), using data listed in table B.1. See table B.1 notes for data sources.*

ID[1]	Location[2]	Calcium Ca (ppm)	Ca/TDS (ppm)	Magnesium Mg (ppm)	Mg/TDS (ppm)	Sodium plus Potassium Na + K (ppm)	Na+K/TDS (ppm)	Sulfate SO_4 (ppm)	SO_4/TDS (ppm)	Chloride Cl (ppm)	Cl/TDS (ppm)	Total Dissolved solids (ppm)	Hardness as $CaCO_3$ (ppm)	H/TDS (ppm)
Northwestern Cedar Valley														
Basin fill														
4	(C-6-2)26cbb-1	36	0.12	30	0.10	20	0.07	27	0.09	19	0.06	298	212	0.71
18	(C-5-2)26bbb-1	80	0.24	14	0.04	21	0.06	37	0.11	34	0.10	337	257	0.76
56	(C-6-1)18dca-1	75	0.18	25	0.06	35	0.08	70	0.17	66	0.16	421	288	0.68
87	(C-6-2)29ccc	59	0.23	20	0.08	8.7	0.03	29	0.11	18	0.07	253	232	0.92
134	(C-6-2)14cac-1	31	0.14	14	0.06	20	0.09	14	0.06	16	0.07	229	134	0.59
1029	(C-6-2)13caa-1	35	0.12	18	0.06	37	0.12	38	0.13	21	0.07	300	160	0.53
1031	(C-6-2)14cba-1	27	0.12	13	0.06	26	0.12	14	0.06	14	0.06	225	120	0.53
1037	(C-6-2)29bdd-1	58	0.25	17	0.07	5.9	0.03	17	0.07	15	0.06	235	215	0.91
1039	(C-6-2)32bbd-1	56	0.19	27	0.09	12	0.04	40	0.14	21	0.07	290	250	0.86
1118	(C-6-2)14dba-1	29	0.11	13	0.05	36	0.14	22	0.09	14	0.06	253	126	0.50
1120	(C-6-2)15bbb-1	80	0.18	32	0.07	14	0.03	36	0.08	78	0.17	451	332	0.74
1121	(C-6-2)15cbb-1	46	0.17	20	0.07	8.6	0.03	23	0.08	17	0.06	273	200	0.73
1123	(C-6-2)15bcb-1	55	0.18	26	0.08	16	0.05	37	0.12	26	0.08	313	244	0.78
1129	(C-8-2)18bcb-1	31	0.08	24	0.06	75	0.19	72	0.18	56	0.14	391	176	0.45
1130	(C-8-2)31adb-1	26	0.06	19	0.04	101	0.23	64	0.14	79	0.18	448	146	0.33
1131	(C-6-2)32cbc-1	67	0.18	30	0.08	31	0.08	49	0.13	29	0.08	380	292	0.77
1132	(C-6-2)33bcb-1	32	0.14	16	0.07	33	0.14	34	0.14	16	0.07	237	146	0.62
S11	(C-6-2)29ccc-1	57	0.22	18	0.07	9.2	0.04	18	0.07	17	0.06	262	214	0.82
	Average	**49**	**0.16**	**21**	**0.07**	**28**	**0.09**	**36**	**0.11**	**31**	**0.09**	**311**	**208**	**0.68**
Bedrock														
S1	(C-4-2)26cbc	77	0.18	10	0.02	41	0.10	33	0.08	76	0.18	431	234	0.54
S2	(C-4-3)20dba	95	0.29	13	0.04	10	0.03	25	0.08	11	0.03	323	290	0.90
S4	(C-4-3)26dda	130	0.23	28	0.05	47	0.08	58	0.10	80	0.14	558	438	0.78
S9	(C-5-3)36cba	62	0.27	16	0.07	2.9	0.01	15	0.07	8	0.04	227	220	0.97
S10	(C-6-2)6cad	88	0.30	12	0.04	5.5	0.02	27	0.09	11	0.04	290	269	0.93
S12	(C-6-3)1aad	65	0.28	16	0.07	4	0.02	17	0.07	8.7	0.04	235	227	0.97
S13	(C-6-3)15bad	67	0.21	29	0.09	12	0.04	38	0.12	20	0.06	321	289	0.90
	Average	**83**	**0.19**	**18**	**0.06**	**17**	**0.07**	**30**	**0.10**	**31**	**0.09**	**341**	**281**	**0.74**
Northeastern Cedar Valley														
Bedrock														
156	N 250 E 200 SW 16 5S 1W	3,600	3.4	70	0.1	9	0.0	233	0.2	293	0.3	1,060	nd	nd
1011	N 100 E 1,420 SW 14 5S 2W	190	0.4	27	0.1	16	0.0	24	0.0	69	0.1	488	nd	nd
1018	N 1,012 W 200 S4 18 6S 1W	70	0.2	28	0.1	14	0.0	70	0.2	63	0.1	422	nd	nd
1023	(C-6-1)31dab-1	82	0.07	116	0.09	179	0.15	291	0.24	355	0.29	1,230	680	0.55
1125	N 25 E 3,100 SW 17 5S 1W	73	0.1	26	0.0	31	0.0	150	0.2	166	0.2	684	nd	nd
1126	S 1,900 W 2,600 NE 30 5S 1W	370	0.6	62	0.1	33	0.1	71	0.1	146	0.2	588	nd	nd
S6	(C-5-1)17bdc	148	0.17	30	0.04	57	0.07	56	0.07	295	0.35	853	494	0.58
	Average	**156**	**0.26**	**51**	**0.07**	**48**	**0.06**	**128**	**0.14**	**198**	**0.24**	**761**	**587**	**0.57**

Table B.2. *(continued)*

Southeastern Cedar Valley														
Basin fill														
1128	(C-7-2)25bdb-1	28	0.01	135	0.07	480	0.24	941	0.47	140	0.07	2,020	625	0.31
1054	(C-7-2)35bcc-1	42	0.02	114	0.07	383	0.22	842	0.48	94	0.05	1,740	575	0.33
1127	(C-8-2)15aad-1	30	0.02	92	0.05	439	0.26	638	0.37	84	0.05	1,710	455	0.27
	Average	**33**	**0.02**	**114**	**0.06**	**434**	**0.24**	**807**	**0.44**	**106**	**0.06**	**1,823**	**552**	**0.30**

Notes

1. Corresponds to labels on figures 11, 12, and 14.
2. Locations given in U.S. Geological Survey or Point of Diversion notation - see figures C.1 or C.2, respectively, for explanation.

Table B.3. *Chemical analyses of samples collected and analyzed by the Utah Department of Agriculture and Food. Wells 56 and 91 are open in bedrock; all others are in basin fill.*

ID[1]	Date of collection	Aluminum Al (mg/L)	Arsenic As (mg/L)	Boron B (mg/L)	Barium Ba (µg/L)	Beryllium Be (µg/L)	Calcium Ca (mg/L)	Cadmium Cd (µg/L)	Chlorine Cl (mg/L)	Cobalt Co (µg/L)	Carbonate CO_3 (mg/L)	Chromium Cr (mg/L)	Copper Cu (µg/L)
82	10/24/2001	bd	bd	bd	0.05	bd	51.1	bd	16.0	bd	bd	bd	bd
70	10/24/2001	bd	bd	bd	0.12	bd	67.2	bd	19.0	bd	bd	bd	bd
84	10/24/2001	bd	bd	bd	0.05	bd	52.6	bd	17.0	bd	bd	bd	bd
20	10/24/2001	bd	bd	0.17	0.11	bd	72.4	bd	42.0	bd	bd	bd	0.03
78	10/24/2001	bd	bd	bd	0.14	bd	81.8	bd	61.0	bd	bd	bd	bd
23	10/24/2001	bd	bd	bd	0.07	bd	65.2	bd	26.0	bd	bd	bd	bd
25	10/24/2001	bd	bd	bd	0.09	bd	66.6	bd	28.0	bd	bd	bd	bd
26	10/24/2001	0.07	bd	0.59	0.03	bd	38.5	bd	138.0	bd	bd	bd	bd
66	10/24/2001	bd	bd	bd	0.05	bd	80.3	bd	34.0	bd	bd	bd	bd
17	10/24/2001	bd	bd	bd	bd	bd	23.7	bd	125.0	bd	bd	bd	0.13
5	10/24/2001	bd	bd	0.09	0.12	bd	122.5	bd	159.0	bd	bd	bd	bd
1026	10/24/2001	bd	bd	bd	0.10	bd	101.7	bd	59.0	bd	bd	bd	bd
60	10/24/2001	bd	bd	0.11	0.08	bd	84.9	bd	24.0	bd	bd	bd	bd
1028	10/24/2001	bd	bd	0.08	0.08	bd	96.7	bd	57.0	bd	bd	bd	bd
56	10/24/2001	bd	bd	0.10	0.09	bd	67.5	bd	72.0	bd	bd	bd	bd
57	10/24/2001	bd	bd	0.20	0.06	bd	30.1	bd	85.0	bd	bd	bd	bd
119	10/24/2001	bd	bd	0.09	0.15	bd	113.9	bd	603.0	bd	bd	bd	bd
139	10/24/2001	bd	bd	0.11	0.07	bd	40.7	bd	48.0	bd	bd	bd	bd
52	10/24/2001	bd	bd	0.09	0.10	bd	31.0	bd	30.0	bd	bd	bd	bd
94	10/24/2001	0.78	bd	0.20	0.13	bd	120.0	bd	220.0	bd	bd	bd	bd
114	10/24/2001	bd	bd	0.11	0.16	bd	130.9	bd	335.0	bd	bd	bd	bd
91	10/24/2001	bd	bd	0.23	0.08	bd	54.3	bd	109.0	bd	bd	bd	bd
1000	10/24/2001	0.12	bd	0.10	0.24	bd	110.9	bd	297.0	bd	bd	bd	bd

Notes

bd - Below detection limit.

1. Corresponds to ID in table C.1.

Table B.3. (continued)

ID[1]	Iron Fe (µg/L)	Bicarbonate HCO_3 (meq/L)	Potassium K (mg/L)	Lithium Li (mg/L)	Magnesium Mg (mg/L)	Manganese Mn (mg/L)	Molybdenum Mo (mg/L)	Sodium Na (mg/L)	Nickel Ni (mg/L)	Nitrate NO_3 (mg/L)	Phosphorus P (mg/L)	Lead Pb (mg/L)	Sulphur S (mg/L)
82	bd	3.34	1.23	bd	20.3	bd	bd	10.1	bd	0.50	bd	bd	7.7
70	0.31	4.52	1.56	bd	25.5	0.04	bd	12.4	bd	0.00	bd	bd	8.6
84	bd	3.55	1.19	bd	22.2	bd	bd	10.9	bd	0.40	bd	bd	9.0
20	bd	5.86	12.25	bd	43.5	bd	bd	26.2	bd	1.00	bd	bd	16.8
78	0.67	4.56	1.79	bd	30.2	0.07	bd	13.3	bd	0.00	bd	bd	8.6
23	0.02	4.25	1.40	bd	28.7	bd	bd	14.3	bd	0.30	bd	bd	14.6
25	bd	4.58	1.63	bd	32.1	bd	bd	17.9	bd	0.20	bd	bd	17.2
26	0.30	6.23	20.13	0.18	79.8	0.06	0.05	180.4	bd	0.00	bd	bd	105.0
66	bd	4.66	1.18	bd	22.3	bd	bd	22.4	bd	1.40	bd	bd	12.9
17	bd	4.33	9.16	bd	38.6	bd	bd	118.6	bd	5.00	bd	bd	21.2
5	0.07	4.87	2.00	bd	38.6	bd	bd	52.5	bd	10.00	bd	bd	31.7
1026	bd	4.91	1.66	bd	30.1	bd	bd	30.1	bd	7.00	bd	bd	23.7
60	0.11	5.20	1.62	bd	26.0	bd	bd	28.4	bd	7.00	bd	bd	13.3
1028	0.08	5.24	1.88	bd	25.8	bd	bd	45.3	bd	7.00	bd	bd	18.3
56	bd	3.53	3.69	0.06	27.1	bd	bd	39.1	bd	0.70	bd	bd	24.7
57	bd	4.58	3.26	0.08	41.6	bd	0.01	88.9	bd	0.40	bd	bd	23.8
119	bd	4.15	1.09	0.13	179.7	0.06	bd	31.5	bd	0.00	bd	bd	17.2
139	0.03	3.08	3.34	bd	22.8	bd	bd	44.6	bd	0.40	bd	bd	18.7
52	0.04	2.33	3.73	bd	21.4	bd	bd	23.6	bd	0.10	bd	bd	15.7
94	0.06	2.50	5.51	bd	37.9	bd	bd	41.3	bd	4.50	bd	0.03	24.9
114	bd	1.96	5.71	bd	45.4	bd	bd	65.2	bd	5.00	bd	bd	22.2
91	0.08	3.45	6.66	0.05	21.4	bd	bd	77.9	bd	0.10	bd	bd	16.7
1000	bd	2.02	8.21	0.07	48.9	bd	bd	49.3	bd	0.10	bd	bd	24.1

Notes

bd - Below detection limit.

1. Corresponds to ID in table C.1.

Table B.3. *(continued)*

ID[1]	Selenium Se (mg/L)	Total Dissolved Solids (mg/L)	Vanadium V (mg/L)	Zinc Zn (mg/L)	Sodium Absoption Ratio	Hardness	Coliform 1=pos 0=neg	ECOLI 1=pos 0=neg	Temperature °C	PH
82	bd	394	bd	0.12	0.30	4.18	0.00	0.00	12	8.0
70	bd	515	bd	bd	0.33	5.42	0.00	0.00	10	8.0
84	bd	427	bd	0.16	0.32	4.37	0.00	0.00	10	8.0
20	bd	721	bd	0.11	0.60	6.78	1.00	0.00	14	8.0
78	bd	632	bd	0.10	0.32	6.55	0.00	0.00	10	8.0
23	bd	524	bd	0.13	0.37	5.49	0.00	0.00	11	8.0
25	bd	568	bd	0.14	0.45	5.77	0.00	0.00	11	8.0
26	bd	1,367	bd	0.06	3.81	6.92	1.00	0.00	13	8.0
66	bd	556	bd	1.94	0.57	6.00	0.00	0.00	12	8.0
17	bd	852	bd	1.23	3.49	3.64	0.00	0.00	14	8.0
5	bd	982	bd	1.08	1.06	9.42	0.00	0.00	17	8.0
1026	bd	940	bd	0.06	0.67	7.71	0.00	0.00	11	8.0
60	bd	624	bd	1.29	0.69	6.49	0.00	0.00	11	8.0
1028	bd	734	bd	0.28	1.06	7.16	0.00	0.00	12	8.0
56	bd	632	bd	bd	1.02	5.53	0.00	0.00	29	8.0
57	bd	783	0.03	0.06	2.46	4.20	0.00	0.00	16	8.0
119	bd	1,898	0.02	bd	0.43	17.17	0.00	0.00	13	8.0
139	bd	464	0.01	1.34	1.39	3.71	0.00	0.00	14	8.0
52	bd	375	0.01	bd	0.80	3.06	0.00	0.00	12	8.0
94	bd	961	bd	4.40	0.84	9.24	0.00	0.00	13	8.0
114	bd	1,205	bd	0.06	1.25	10.31	0.00	0.00	13	7.0
91	bd	704	bd	0.97	2.27	4.43	0.00	0.00	13	8.0
1000	bd	1,150	0.01	0.15	0.98	9.34	0.00	0.00	14	8.0

Notes

bd - Below detection limit.

1. Corresponds to ID in table C.1.

Table B.4. *Ratios of selected species concentrations to total dissolved solids (TDS), using data from the Utah Department of Agriculture and Food listed in table B.3. Wells 56 and 91 are open in bedrock; all others are in basin fill.*

ID[1]	Calcium Ca (mg/L)	Ca/TDS (mg/L)	Magnesium Mg (mg/L)	Mg/TDS (mg/L)	Sodium plus Potassium Na + K (mg/L)	Na+K/TDS (mg/L)	Sulfur S (mg/L)	S/TDS (mg/L)	Chlorine Cl (mg/L)	Cl/TDS (mg/L)	Total Dissolved Solids (mg/L)	Hardness as $CaCO_3$ (mg/L)	H/TDS (mg/L)
Northwestern Cedar Valley													
5	122.5	0.12	38.6	0.04	54.5	0.06	31.7	0.03	159.0	0.16	982	9.42	0.01
17	23.7	0.03	38.6	0.05	127.7	0.15	21.2	0.02	125.0	0.15	852	3.64	0.00
20	72.4	0.10	43.5	0.06	38.4	0.05	16.8	0.02	42.0	0.06	721	6.78	0.01
23	65.2	0.12	28.7	0.05	15.7	0.03	14.6	0.03	26.0	0.05	524	5.49	0.01
25	66.6	0.12	32.1	0.06	19.5	0.03	17.2	0.03	28.0	0.05	568	5.77	0.01
66	80.3	0.14	22.3	0.04	23.6	0.04	12.9	0.02	34.0	0.06	556	6.00	0.01
60	84.9	0.14	26.0	0.04	30.1	0.05	13.3	0.02	24.0	0.04	624	6.49	0.01
70	67.2	0.13	25.5	0.05	14.0	0.03	8.6	0.02	19.0	0.04	515	5.42	0.01
78	81.8	0.13	30.2	0.05	15.1	0.02	8.6	0.01	61.0	0.10	632	6.55	0.01
82	51.1	0.13	20.3	0.05	11.3	0.03	7.7	0.02	16.0	0.04	394	4.18	0.01
84	52.6	0.12	22.2	0.05	12.1	0.03	9.0	0.02	17.0	0.04	427	4.37	0.01
1026	101.7	0.11	30.1	0.03	31.8	0.03	23.7	0.03	59.0	0.06	940	7.71	0.01
1028	96.7	0.13	25.8	0.04	47.1	0.06	18.3	0.02	57.0	0.08	734	7.16	0.01
Average	**74.4**	**0.12**	**29.5**	**0.05**	**33.9**	**0.05**	**15.6**	**0.02**	**51.3**	**0.07**	**651.5**	**6.1**	**0.01**
North-central Cedar Valley													
119	113.9	0.06	179.7	0.09	32.6	0.02	17.2	0.01	603.0	0.32	1,898	17.17	0.01
Northeastern Cedar Valley													
26	38.5	0.03	79.8	0.06	200.6	0.15	105.0	0.08	138.0	0.10	1,367	6.92	0.01
56	67.5	0.11	27.1	0.04	42.8	0.07	24.7	0.04	72.0	0.11	632	5.53	0.01
91	54.3	0.08	21.4	0.03	84.5	0.12	16.7	0.02	109.0	0.15	704	4.43	0.01
94	120.0	0.12	37.9	0.04	46.8	0.05	24.9	0.03	220.0	0.23	961	9.24	0.01
1000	110.9	0.10	48.9	0.04	57.5	0.05	24.1	0.02	297.0	0.26	1,150	9.34	0.01
114	130.9	0.11	45.4	0.04	70.9	0.06	22.2	0.02	335.0	0.28	1,205	10.31	0.01
139	40.7	0.09	22.8	0.05	47.9	0.10	18.7	0.04	48.0	0.10	464	3.71	0.01
52	31.0	0.08	21.4	0.06	27.4	0.07	15.7	0.04	30.0	0.08	375	3.06	0.01
57	30.1	0.04	41.6	0.05	92.2	0.12	23.8	0.03	85.0	0.11	783	4.20	0.01
Average	**69.3**	**0.08**	**38.5**	**0.05**	**74.5**	**0.09**	**30.7**	**0.04**	**148.2**	**0.16**	**849**	**6.3**	**0.01**

Notes

1. Corresponds to ID in table C.1

APPENDIX C

Well data

ID[1]	Location[2]	Depth to bedrock
1	N 1,920 W 1,200 SE 25 4S 3W	55
2	N 300 W 2,400 SE 21 5S 1W	85
3	S 355 E 97 NW 9 10S 2W	0
4	S 64 E 57 W4 26 6S 2W	>505
5	N 1,131 E 1,050 5 SW 6S 2W	>204
6	N 1,500 W 300 SE 36 7S 2W	402
7	N 2,800 W 4,000 SE 31 5S 1W	52
8	N 100 W 1,220 E4 9 6S 2W	>225
9	S 1,656 W 424 N4 9 6S 2W	>210
10	N 2,333 W 1,104 SE 6 6S 2W	>202
11	N 400 W 500 SE 6 6S 2W	>281
12	N 575 E 1,090 S4 6 6S 2W	287
13	N 60 W 230 E4 6 6S 2W	>274
14	S 1,175 W 511 E4 6 6S 2W	>310
15	S 1,150 W 600 NE 6 6S 2W	>215
16	N 930 W 1,160 E4 6 6S 2W	>200
17	N 170 W 630 SE 6 6S 2W	>195
18	S 20 E 50 NW 26 5S 2W	>448
19	N 150 E 150 W4 28 7S 2W	>305
20	S 45 E 1,410 N4 32 6S 2W	>285
21	S 312 E 3,466 NW 32 6S 2W	>341
22	S 310 W 550 N4 32 6S 2W	>30
23	S 540 W 740 N4 32 6S 2W	>210
24	S 223 W 355 NE 32 6S 2W	>196
25	N 100 E 900 W4 32 6S 2W	>125
26	S 256 W 907 E4 31 6S 1W	uncertain
27	N 1,356 W 1,006 SE 18 6S 1W	>235
28	N 1,579 W 1,788 S4 17 6S 2W	>147
29	S 80 E 180 N4 16 6S 2W	>505
30	N 1,530 W 820 S4 29 6S 2W	>266
31	N 1,375 W 730 S4 29 6S 2W	>253
32	N 1,537 E 1,292 S4 29 6S 2W	>253
33	S 195 E 75 NW 25 5S 2W	>473
34	S 0 E 2,700 NW 33 6S 2W	>180
35	S 0 W 2,640 NE 25 6S 2W	>505
36	N 1,077 E 332 SW 28 6S 2W	>300
37	S 760 W 1,320 N4 33 6S 2W	>280
38	N 1,790 W 1,930 SE 33 6S 2W	>302
39	N 1,400 E 750 S4 6 6S 1W	393
40	N 210 W 150 S4 25 7S 2W	>200
41	S 20 E 1,300 NW 19 6S 1W	>590
42	S 750 E 150 NW 11 7S 2W	>100
43	S 1,350 E 2,300 NW 6 6S 2W	160
44	N 526 E 40 S4 17 6S 2W	>595
45	N 1,320 E 1,320 SW 27 6S 2W	>80
46	N 180 W 125 S4 6 6S 2W	>230
47	N 300 E 300 SW 3 6S 2W	>300
49	N 1,120 W 1,030 SE 29 6S 2W	>281

Table C.1. *(continued)*

ID[1]	Location[2]	Depth to bedrock
50	S 114 E 2,886 W4 7 6S 1W	>755
51	N 590 W 590 E4 6 6S 2W	>230
52	S 385 E 3,611 W4 17 6S 1W	>510
53	N 850 W 970 S4 5 6S 2W	>200
54	N 1,400 E 2,600 SW 7 7S 1W	<147
55	N 100 W 2,300 SE 6 6S 2W	211
56	N 776 W 291 S4 18 6S 1W	369
57	S 200 E 1,150 N4 30 6S 1W	>335
58	S 730 W 170 N4 30 6S 1W	>300
59	S 310 E 1,100 NW 28 5S 1W	125
60	S 1,780 E 1,890 N4 6 6S 2W	>235
61	S 300 E 400 NW 5 7S 2W	>280
62	N 2,200 W 1,100 SE 6 6S 1W	191
63	N 1,350 E 2,100 SW 29 7S 2W	>400
64	S 1,250 W 2,600 NE 19 5S 1W	>280
65	S 578 E 88 N4 32 6S 2W	>267
66	N 1,600 W 2,400 SE 6 6S 2W	206
67	N 925 W 40 S4 6 6S 2W	55
68	S 200 W 660 NE 32 5S 2W	396
69	N 520 E 1,130 S4 29 6S 2W	>259
70	N 250 E 1,150 S4 29 6S 2W	>217
71	S 460 W 1,250 NE 32 6S 2W	>242
72	N 2,130 E 270 SW 5 6S 2W	207
73	N 300 W 1,200 SE 6 6S 2W	>320
74	S 200 E 500 NW 23 6S 2W	>578
75	S 175 E 869 N4 7 6S 1W	351
76	N 2,600 E 200 SW 18 7S 1W	190
77	N 840 W 279 S4 18 6S 1W	349
78	N 200 W 1,140 SE 29 6S 2W	>254
79	N 137 E 144 W4 28 6S 2W	>285
80	S 7 W 6 NE 33 7S 2W	>405
81	S 10 E 860 W4 17 5S 1W	>139
82	N 490 W 610 S4 29 6S 2W	>217
83	N 500 W 490 S4 29 6S 2W	>254
84	S 150 E 2,700 NW 32 6S 2W	>286
85	N 1,764 W 931 SE 13 5S 3W	23
86	N 1,500 W 2,600 SE 2 7S 3W	57
87	N 436 E 178 SW 29 6S 2W	>242
88	S 250 E 900 NW 20 5S 1W	>298
89	N 600 E 300 SW 17 5S 1W	>258
90	S 300 W 200 NE 19 5S 1W	>405
91	S 300 W 900 NE 19 5S 1W	>255
92	S 300 W 1,300 NE 19 5S 1W	>380
93	S 300 W 1,650 NE 19 5S 1W	>320
94	S 300 W 2,100 NE 19 5S 1W	>325
95	S 600 W 2,400 NE 19 5S 1W	>400
96	S 1,000 W 2,300 NE 19 5S 1W	277
97	S 1,250 W 3,600 NE 19 5S 1W	119
98	N 100 W 120 SE 13 5S 2W	193
99	S 1,500 W 3,900 NE 19 5S 1W	437
100	S 1,700 W 3,500 NE 19 5S 1W	189
101	S 1,700 W 3,000 NE 19 5S 1W	131

Table C.1. *(continued)*

ID[1]	Location[2]	Depth to bedrock
102	S 2,150 W 1,400 NE 19 5S 1W	139
103	S 2,400 W 750 NE 19 5S 1W	80
104	S 2,250 W 2,750 NE 19 5S 1W	18
105	S 2,250 W 3,450 NE 19 5S 1W	21
106	S 2,900 W 4,800 NE 19 5S 1W	54
107	S 2,900 W 4,300 NE 19 5S 1W	67
108	S 2,900 W 3,800 NE 19 5S 1W	54
109	S 2,400 W 250 NE 19 5S 1W	127
110	S 1,700 W 700 NE 19 5S 1W	148
111	S 1,600 W 1,100 NE 19 5S 1W	175
112	S 1,500 W 1,400 NE 19 5S 1W	>260
113	S 900 W 1,600 NE 19 5S 1W	>238
114	S 950 W 1,150 NE 19 5S 1W	>307
115	S 1,000 W 700 NE 19 5S 1W	>195
116	S 1,100 W 150 NE 19 5S 1W	>258
117	S 50 E 660 N4 19 7S 1W	>305
118	N 1,370 E 50 SW 23 7S 2W	>275
119	N 70 E 300 SW 23 6S 2W	>467
120	S 2,900 W 300 NE 19 5S 1W	96
121	S 4,050 W 1,700 NE 19 5S 1W	14
122	N 500 E 2,800 SW 19 5S 1W	22
123	N 1,350 E 3,000 SW 19 5S 1W	18
124	N 1,500 E 2,650 SW 19 5S 1W	8
125	N 1,950 E 3,300 SW 19 5S 1W	29
126	N 2,450 E 2,500 SW 19 5S 1W	49
127	N 300 E 3,850 SW 19 5S 1W	27
128	S 2,000 W 600 NE 24 5S 2W	>480
129	S 900 W 2,400 NE 24 5S 2W	562
130	N 280 E 2,300 W4 32 6S 2W	>279
131	N 70 E 300 W4 23 6S 2W	>324
132	S 376 E 146 N4 5 6S 2W	>269
133	S 2,400 E 1,800 NW 5 6S 2W	>269
134	N 1,319 E 1,689 SW 14 6S 2W	>1250
135	S 830 E 1,250 N4 6 6S 2W	>320
136	S 30 W 700 NE 19 5S 1W	175
137	S 2,600 W 800 NE 19 5S 1W	15
138	N 150 W 300 SE 6 6S 2W	>285
139	S 385 E 3,911 W4 7 6S 1W	uncertain
140	S 1,140 E 25 NW 17 6S 2W	>320
141	N 1,000 E 900 SW 17 5S 1W	>265
142	S 300 W 550 NE 19 5S 1W	>400
143	N 380 W 480 SE 6 6S 2W	220
144	N 900 W 700 SE 6 6S 2W	>305
145	N 1,250 E 450 SW 28 5S 2W	<279
146	S 125 E 300 N4 15 5S 1W	>253
147	N 104 W 2,514 E4 15 5S 1W	>260
148	N 365 E 2,750 W4 15 5S 1W	>280
149	S 369 E 319 N4 15 5S 1W	82
150	S 1,130 W 910 NE 15 5S 1W	>256
151	N 2,100 W 800 SE 16 5S 1W	11
152	N 1,000 W 150 SE 16 5S 1W	0
153	N 2,000 W 100 SE 16 5S 1W	3

Table C.1. *(continued)*

ID[1]	Location[2]	Depth to bedrock
154	N 1,350 W 980 SE 16 5S 1W	2
155	N 1,980 W 980 SE 16 5S 1W	9
156	N 250 E 200 SW 16 5S 1W	80
157	N 800 W 280 SE 16 5S 1W	6
158	N 2,000 E 1,500 SW 16 5S 1W	6
159	N 500 E 2,400 W4 16 5S 1W	27
160	S 3,700 W 1100 NE 19 5S 1W	35
161	S 2,800 W 1,600 NE	65
162	S 2,500 W 250 NE 19 5S 1W	97
163	S 2,500 E 150 N4 23 5S 1W	95
164	N 1,200 W 500 S4 23 5S 1W	>121
165	S 90 E 1,369 W4 23 5S 1W	>160
166	N 234 E 2,059 W4 23 5S 1W	>115
167	N 500 W 250 S4 23 5S 1W	>125
168	N 625 W 250 S4 23 5S 1W	>125
169	S 1,490 W 60 N4 23 5S 1W	>162
170	N 754 E 2,997 W4 23 5S 1W	>180
171	N 135 E 2,997 W4 23 5S 1W	>205
172	S 4,806 W 5,271 NE 25 5S 1W	>84
173	S 1,860 W 814 N4 26 5S 1W	396
174	N 1,500 E 4,840 SW 27 5S 1W	>335
175	N 649 E 873 S4 31 5S 2W	>325
176	N 1,800 E 3,600 SW 29 6S 1E	>221
177	S 29 E 2,611 NW 30 6S 1E	195
178	N 150 E 1,430 SW 7 6S 1E	>103
179	S 1,370 E 750 NW 18 6S 1E	>300
180	N 300 E 400 S4 18 6S 1E	>110
181	N 940 E 220 W4 18 6S 1E	>180
182	N 430 E 520 W4 18 6S 1E	>180
183	N 400 E 2,800 SW 18 6S 1E	>160
184	N 150 E 1,765 S4 18 6S 1E	uncertain
185	S 2,600 E 1,300 NW 19 6S 1E	>351
186	N 1,080 W 930 E4 31 6S 1E	80
188	N 737 E 1,814 SW 26 7S 1W	>190
189	N 2,640 E 1 S4 30 7S 3W	>300
190	S 2,155 W 208 NE 19 8S 1W	uncertain
192	N 575 E 1,547 SW 20 8S 1W	205
193	N 1 W 2,640 E4 29 8S 1W	>205
194	S 528 E 1,056 N4 32 8S 1W	150
195	N 28 E 375 W4 34 8S 1W	>412
196	S 4,143 W 220 NE 20 9S 1W	>575
197	N 1,035 E 738 S4 26 9S 1W	>31
198	N 367 E 1,277 W4 2 10S 1W	>100
199	S 66 E 90 W4 4 10S 1W	284
1000	N 200 E 300 SW 17 5S 1W	>255
1001	N 2,702 E 5,168 W4 21 4S 2W	45
1002	S 342 E 9,516 SW 18 5S 1W	60
1003	S 1,100 W 2,500 NE 18 5S 1W	300
1004	N 740 E 950 S4 18 5S 1E	>159
1005	S 1,300 W 1,800 NE 19 5S 1W	>225
1006	S 3,200 W 900 NE 19 5S 1W	13
1007	N 500 E 820 S4 19 5S 1W	>40

Table C.1. *(continued)*

ID[1]	Location[2]	Depth to bedrock
1008	N 110 E 750 SE 20 5S 1W	70
1009	S 100 W 300 N4 26 5S 1W	247
1010	S 700 W 1,000 NE 7 5S 2W	20
1011	N 100 E 1,420 SW 14 5S 2W	40
1012	N 2,310 W 612 S4 1 5S 3W	>210
1013	S 100 W 200 N4 20 5S 3W	12
1014	N 100 E 700 SW 32 5S 3W	0
1015	N 500 E 3,400 SW 32 5S 3W	12
1016	N 2,000 W 1,930 SE 12 6S 1W	180
1017	N 2,000 W 1,900 SE 12 6S 1W	>205
1018	N 1,012 W 200 S4 18 6S 1W	349
1020	S 1,245 W 535 N4 20 6S 1W	185
1021	S 175 W 969 NE 29 6S 1W	0
1022	S 2,400 E 1,050 NW 30 6S 1E	272
1023	S 264 W 957 E4 31 6S 1W	193
1024	S 2,000 W 2,500 NE 1 6S 2W	>300
1025	N 1,696 W 1,300 S4 4 6S 2W	83
1026	N 1,180 E 950 SW 5 6S 2W	>190
1027	S 730 E 2,530 W4 5 6S 2W	>430
1028	S 1,200 W 800 NE 6 6S 2W	213
1029	N 2,170 W 10 S4 13 6S 2W	>525
1030	N 1,300 W25 SE 13 6S 2W	1071
1031	N 2,640 E 30 SW 14 6S 2W	>1007
1032	S 1,050 E 10 NW 17 6S 2W	>292
1033	S 1,035 W 38 NE 18 6S 2W	462
1034	N 400 W 3,700 SE 19 6S 2W	>35
1035	S 60 E 60 N4 20 6S 2W	>600
1036	N 100 E 100 SW 24 6S 2W	>110
1037	SE4 OF NW4 29 6S 2W	>654
1038	N 2,630 W 2,600 32 6S 2W	>365
1039	S 608 E 1,300 NW 32 6S 2W	>613
1040	S 1,320 E 1,320 NW 34 6S 2W	>275
1041	S 3,109 W 1,157 NE 34 5S 2W	>280
1042	S 1,320 E 0 NW 36 6S 2W	>500
1043	N 1,450 E 400 SW 4 6S 3W	65
1044	N 1,400 E 400 SE 3 6S 3W	65
1045	N 2,600 E 150 SE 3 6S 3W	17
1046	N 2,720 E 200 SE 3 6S 3W	0
1047	S 240 E 700 NW 5 6S 3W	0
1048	N 50 E 200 NE 5 6S 3W	0
1049	N 50 E 50 NE 6 6S 3W	0
1050	N 610 E 280 SE 12 6S 3W	200
1051	S 2,200 W 1,300 NE 13 7S 1W	103
1052	N 520 E 2,550 SW 26 7S 1W	>125
1053	N 8,460 W 10,560 SW 30 7S 1W	>220
1054	S 2,400 W 10,660 SW 30 7S 1W	>190
1055	N 1,105 E 58 SW 4 8S 1W	87
1056	N 2,178 W 2,293 E4 17 8S 1W	60
1057	N 850 E 1,810 SW 20 8S 1W	207
1058	S 1,300 E 30 W4 20 8S 1W	20
1059	S 2,250 E 1,810 NW 29 8S 1W	320
1060	N 1,200 W 60 SE 29 8S 1W	307

Table C.1. (continued)

ID[1]	Location[2]	Depth to bedrock
1062	N 33 W 528 SE 18 8S 2W	>350
1063	N 1,752 W 1,080 SE 25 8S 2W	>600
1064	N 1,030 W 1,440 SE 29 8S 2W	>183
1065	N 2,279 E 3,813 SW 35 8S 2W	>235
1066	N 240 E 1,524 SW 6 8S 3W	275
1067	N 2,194 S 1,320 NE 7 8S 3W	290
1068	N 1,100 E 1,000 SW 29 8S 3W	>275
1069	N 1,630 E 1,120 SW 29 8S 3W	>278
1070	S 45 E 1,280 W4 5 9S 2W	>157
1071	S 1,847 W 250 N4 6 9S 2W	>183
1072	N 960 E 420 SW 8 9S 2W	65
1073	S 700 E 130 W4 14 9S 2W	>155
1074	N 30 E 1,030 SW 2 9S 1E	0
1075	N 10 W 1,320 SW 3 9S 1W	>690
1076	N 600 W 1,000 SE 5 9S 1W	284
1077	N 20 W 50 S4 8 9S 1W	82
1078	S 1,900 E 1,300 NW 17 9S 1W	>50
1079	N 1,132 E 100 SW 24 9S 1W	>798
1080	N 3,200 E 2,200 SW 26 9S 1W	63
1081	S 66 E 90 W4 28 9S 1W	>802
1082	N 200 E 50 SW 34 9S 1W	>381
1083	N 600 W 600 SE 34 9S 1W	>265
1084	S 535 W 330 N4 35 9S 1W	>35
1085	N 522 W 528 NE 35 9S 1W	>34
1086	N 2,000 W 3,400 SE 9 10S 3W	>380
1088	N 10 W 1,320 E4 27 9S 1W	>103
1089	S 100 W 1,170 NE 36 8S 4W	>1002
1090	N 1,400 E 2,870 SW 29 6S 1E	>140
1091	S 735 E 300 NW 5 7S 1E	9
1092	N 530 E 40 SW 5 7S 1E	15
1093	S 2,940 E 150 N4 18 7S 1E	>173
1094	S 528 E 1,056 N4 32 8S 1W	150
1095	S 200 W 350 NE 19 8S 1W	120
1096	N 1,125 W 400 SE 29 8S 1W	>236
1097	S 0 W 1,225 E4 30 8S 1W	165
1098	S 13,200 E 1,050 NW 32 8S 1W	335
1099	N 600 E 3,340 SW 35 8S 1W	>212
1100	S 2,600 W 350 NE 32 8S 1W	673
1101	N 1,900 E 600 S4 32 8S 1W	550
1102	N 34 W 1,180 S4 5 5S 1W	25
1103	N 400 W 1,550 SE 5 5S 1W	>168
1104	S 1,050 W 1,200 NE 15 5S 1W	>231
1105	S 2,540 E 140 N4 15 5S 1W	>257
1106	S 900 W 325 NE 15 5S 1W	>235
1107	S 1,465 W 90 N4 23 5S 1W	>102
1109	N 375 W 250 S4 23 5S 1W	>131
1110	N 150 W 1,100 S4 23 5S 1W	>1110
1111	N 1,061 E 5,717 SW 26 5S 1W	>147
1112	N 720 E 10 W4 27 5S 1W	>121
1113	(C-5-2)24aaa-1	60
1114	S 50 E 1,300 NE 13 6S 2W	>1258
1115	S 550 W 65 NE 22 6S 3W	>100

Table C.1. *(continued)*

ID[1]	Location[2]	Depth to bedrock
1116	N 730 E 990 SE 10 6S 3W	20
1117	(C-6-2)27ccc-1	>505
1118	N 2,697 E 3,128 SW 14 6S 2W	>810
1119	N 1,242 E 123 SW 15 5S 2W	468
1120	S 100 E 50 NW 15 6S 2W	>475
1121	S 2,640 E 50 NW 15 6S 2W	>455
1122	S 93 E 2,640 NW 15 6S 2W	2042
1123	S 1,320 E 60 NW 15 6S 2W	>955
1124	(C-6-2)14aba-1	>1254
1125	N 25 E 3,100 SW 17 5S 1W	135
1126	S 1,900 W 2,600 NE 30 5S 1W	35

Notes

1. Corresponds to water-well labels on plate 3 and ID referenced in text.
2. Locations given in U.S. Geological Survey or Point of Diversion notation - see figures C.1 and C.2, respectively, for explanations.
3. Estimated depth to bedrock based on well drillers' logs. Logs are available from the Utah Division of Water Rights Web site (<http://www.waterrights.utah.gov>)

Table C.2. *Records of petroleum-exploration wells in Cedar Valley, Utah County study area[1].*

ID[2]	Operator	Well Name	API Number	Township	Range	Section	Spot[3]	Elevation	Depth	Log[4]
OW1	INTERMOUNTAIN NAT RES	2 RUSH VALLEY	4304530007	7S	3S	20	576 FNL 343 FEL	5,300	1,209	IPo 181; IPMmc 400
OW2	INTERMOUNTAIN NAT RES	4 RUSH VALLEY EAST	4304530009	7S	3S	21	500 FNL 1820 FWL	5,300	1,042	IPMmc 470
OW3	ROCKWELL OIL CO	22-1 ROCKWELL	4304530011	8S	3S	22	660 FSL 660 FWL	5,272	2,313	-
OW4	ROCKWELL OIL CO	27-3 ROCKWELL	4304530012	8S	3S	27	1,980 FNL 760 FWL	5,283	745	-
OW5	UTAH OIL COMPANY	1 LAKE HILLS	4304920059	6S	1S	2	1,980 FNL 500 FWL	4,818	405	-
OW6	COLLINS BROTHERS OIL CO	1 WARD-WEBB-FEE	4304910218	5S	1S	16	660 FSL 660 FEL	4,808	3,514	Mh 1,550; Md 2,330; Mg 3,100

Notes

1. Data from Utah Division of Oil, Gas and Mining records.
2. Corresponds to petroleum-well labels on figures 8 and 16, and plate 1.
3. Distances in feet from north (FNL), south (FSL), east (FEL), and west (FWL) section boundaries.
4. Values are depth to top of formation in feet below reference elevation. Abbreviations are geologic map symbols shown on figures 7 and 8 and plate 1.

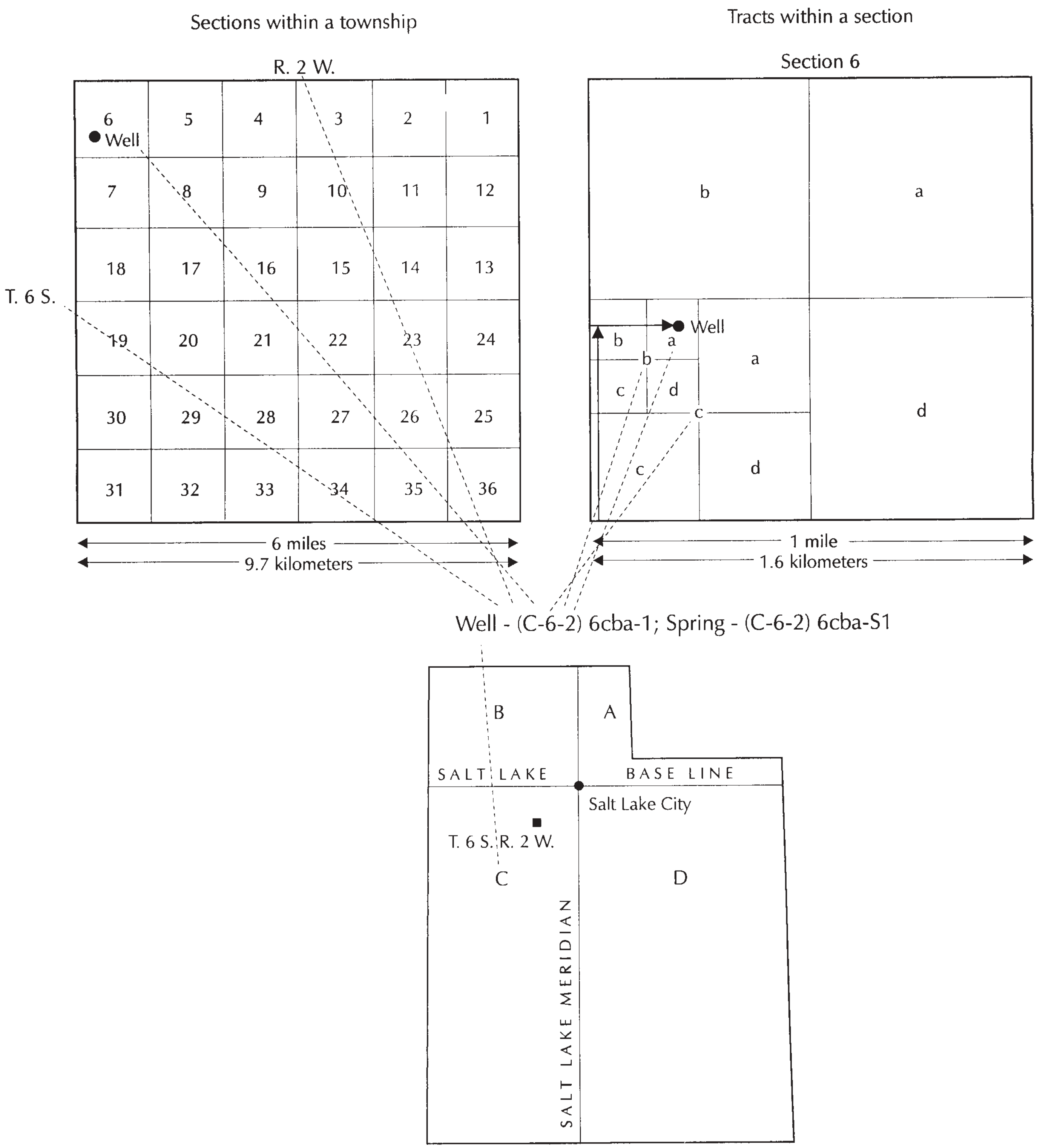

Figure C.1. *Numbering system for wells and springs in Utah - U.S. Geological Survey convention.*

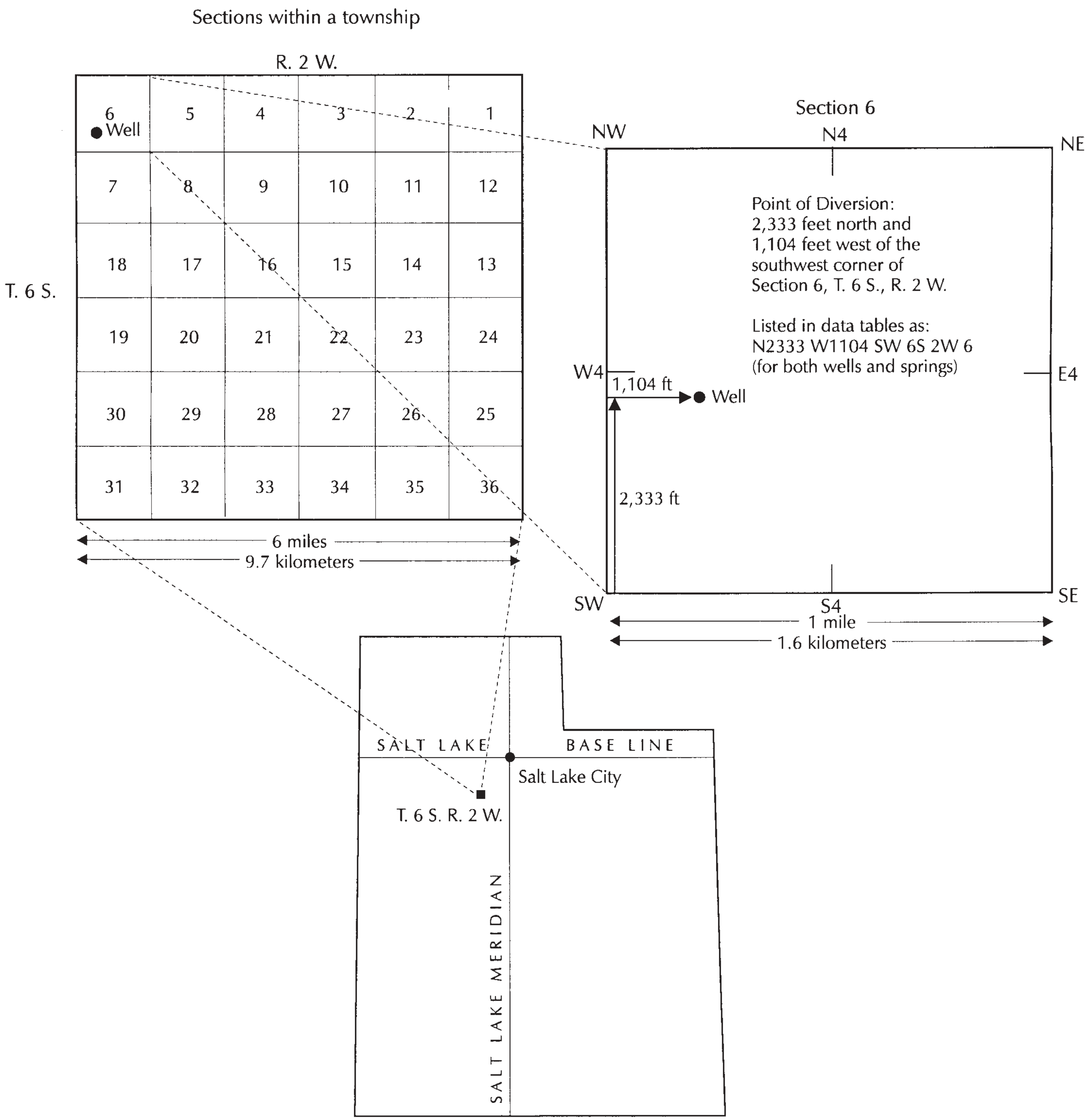

Figure C.2. *Numbering system for wells and springs in Utah - Point of diversion convention.*

APPENDIX D

Methods, results, and interpretation of seismic-refraction surveys

by

Hugh A. Hurlow and Charles E. Bishop

INTRODUCTION

We performed three reconnaissance seismic-refraction surveys in the area between Fairfield Spring and the irrigation wells to gain information on subsurface geology and its influence on hydrogeology (figures D.1 and 16). The survey consisted of three west-to-east traverses; the northern two crossed an imaginary line connecting the wells and the spring, and the southernmost was just south of the spring (figures D.1 and 17).

As applied in this project, the seismic-refraction technique involves generating compressional seismic waves on the land surface and measuring their travel through the subsurface. The seismic waves travel downward into the shallow subsurface at a velocity that depends on the density, porosity, lithology, and degree of saturation of the sediment and rock. When the seismic waves encounter abrupt changes in velocity, such as when encountering a change in sediment type, rock type, or the water table, some waves travel along the discontinuity and then return to the surface (refracted waves) and some continue downward. These refracted waves and waves traveling horizontally just below the surface are recorded by geophones deployed in a linear array at the surface. The geophones convert the vertical component of the ground motion caused by the seismic waves into electrical signals that are recorded and stored for processing.

Data interpretation involves plotting the first arrival times of the seismic waves as a function of distance from the source (time-distance plots). The arrival times depend on the velocity at which the waves travel through the sediment or rock, and on the depth of the velocity discontinuities causing the refraction. Analysis of the time-distance plots lead to interpretations of the seismic-wave velocity of subsurface geologic units and the positions and inclinations of their contacts. The seismic-wave source, geophone spacing, and number of geophones used in this study allowed us to interpret the velocity structure to depths of about 200 feet (60 m). Our objective was to record abrupt lateral changes in velocity, corresponding to a displaced contact or sediments of different velocities juxtaposed across a fault.

METHODS

Each traverse consisted of multiple refraction lines connected end-to-end (figures D.2 through D.4). Traverse S1 was 8,300 feet (2,530 m) long, consisted of 13 refraction lines, and crossed the imaginary line between Fairfield Spring and the irrigation wells about 0.5 mile (0.8 km) south of the wells (figure D.1). Traverse S2 was 3,000 feet (914 m) long, consisted of five refraction lines, and crossed the imaginary line about halfway between the spring and the wells. Traverse S3 was 3,000 feet (914 m) long, consisted of five refraction lines, and was located just south of Fairfield Spring. For each refraction line, 10 or 12 geophones spaced 50 feet (15 m) apart were deployed along a linear array with end-on shot gathers, near offset (source to first geophone) of 50 feet (15 m), and far offset (source to last geophone) of 650 feet (198 m) or 550 feet (168 m). To generate the seismic waves we used a Bison EWG (elastic-wave generator) 700-pound (318 kg) enhanced weight-drop mechanism, borrowed from the University of Utah Department of Geology and Geophysics. We used a multichannel EG&G Geometrics Model ES-1225 exploration seismograph for data collection, and processed the data using the program SeisView (EG&G Geometrics, Inc., 1986). Three to five separate impacts from the EWG were stacked (summed), to enhance the signal of refracted seismic waves and reduce random noise. We recorded shots at both ends of each line, to aid in the interpretation of the dip of contacts and the location of displaced contacts.

INTERPRETATION

Our interpretations of the three seismic-refraction traverses yield the generalized velocity structure and geology along the traverses to about 200 feet (60 m) depth (figures D.2 through D.4). Generally, the velocity models indicate a near-surface, low-velocity layer having seismic velocities of 1,460 to 3,720 feet per second (450-1,130 m/s), overlying higher velocity sediments and/or volcanic rocks and bedrock with seismic velocities of 3,260 to 10,970 feet per second (990-3,340 m/s) along a sharp velocity discontinuity. The contact between these layers is a gently east-sloping velocity discontinuity about 20 to 100 feet (6-30 m) below the land surface. This sloping discontinuity does not display an abrupt lateral change in elevation that could be interpreted as a fault.

The velocity interpretations in figures D.2 through D.4 show abrupt changes in the depth of the velocity discontinuity at the endpoints of many of the refraction lines. The interpreted velocities for each refraction line represent values averaged over a range of depth and over the entire line length. Geologic properties that affect seismic-wave velocity, such as sediment type and compaction with depth, vary gradually and should not be expected to coincidentally change abruptly at or near the refraction-line boundaries. The abrupt changes in average velocity in adjacent refraction lines are interpreted to reflect differences in average properties caused by gradual, lateral changes in sediment type. The apparent offsets in the depth of the discontinuity at the ends of adjacent refraction lines may also in part reflect changes in recording conditions and/or interpretation of the time-distance plots rather than geologic features. These offsets are, therefore, smoothed in the geologic interpretations of the velocity profiles.

Traverse S1 (figure D.2) displays: (1) an upper layer with a velocity range of about 1,450 to 2,700 feet per second (440-820 m/s) from the land surface to about 10 to 100 feet (3-30 m) depth, (2) an intermediate layer with a velocity range of about 3,500 to 4,980 feet per second (1,070-1,520 m/s) that is 0 to about 100 feet (30 m) thick and is absent in the western third of the profile, and (3) a lower layer with a velocity range of about 8,000 to 11,000 feet per second (2,440-3,350 m/s) that extends below the depth resolution of the traverse. The velocity of the upper layer is consistent with typical values for unconsolidated, unsaturated, and coarse-grained deposits, and with the lower velocity ranges of saturated sand and clay (Jakosky, 1950). Water-well logs for the area indicate mixed coarse- and fined-grained sediment to approximately 100 feet (30 m) depth (cross sections G-G' and J-J', plate 3B). Water levels in wells in and near the area in question are about 2 to 100 feet (0.6-30 m) below the land surface; first water was encountered at about 60 to 100 feet (20-30 m) depth, based on well logs available from the Utah Division of Water Rights (<http://www.waterrights.utah.gov>).

We interpret the upper layer in traverse S1 as unsaturated Quaternary gravel, sand, and clay (figure D.2). This layer corresponds to geologic map units Qafy and Qlf (plate 1) and represents the youngest basin-fill deposits in Cedar Valley. In the western third of the traverse, these deposits overlie high-velocity material that we interpret to be limestone and sandstone of the Oquirrh Group. The velocity range of the lower layer is consistent with laboratory measurements on limestone and quartzite (Jakosky, 1950). Two small-displacement faults are imaged in the western third of the traverse (figure D.2). These faults are indicated in the refraction profiles by abrupt changes in the slope of the time-distance plots within, not at the edges of, the refraction lines.

The nature of the velocity discontinuity at the base of the upper layer and the identity of the middle layer in traverse S1 are uncertain (figure D.2). The discontinuity may be a contact between younger and older, semi-consolidated basin-fill deposits, or it may represent the contact between saturated and unsaturated basin-fill sediment. The velocity range of the middle layer is consistent with either interpretation. The shallow water table, as indicated by the depth to first water in the wells mentioned above, is at about the same depth as the discontinuity where it occurs within basin-fill deposits. We interpret the velocity discontinuity at the base of the upper layer in the western third of the traverse to represent the contact between late Quaternary alluvial-fan deposits and Paleozoic bedrock, and to represent the contact between younger and older basin-fill deposits in the eastern two-thirds of the traverse (figure D.2). Layer 2 may also be the boundary between saturated and unsaturated sediment within gradational alluvial-fan and lacustrine deposits. We favor the former interpretation based on the results of traverses S2 and S3 (figures D.3 and D.4).

Traverse S2 (figure D.3) displays an upper layer with a velocity range of about 2,880 to 3,700 feet per second (880-1,130 m/s) and a lower layer with a velocity range of about 4,400 to 6,700 feet per second (1,340-2,040 m/s). Traverse S3 (figure D.4) displays an upper layer with a velocity range of about 2,350 to 3,400 feet per second (720-1,040 m/s) and a lower layer with a velocity range of about 4,900 to 6,250 feet per second (1,490-1,910 m/s). The discontinuity between the upper and lower layers in both traverses is smooth, gently east sloping, and is located at about 60 to 100 feet deep (18-30 m). This discontinuity is at similar depth and has a similar form to the discontinuity between low and intermediate-velocity layers imaged in the eastern part of traverse S1, and likely represents the same surface in all three traverses. Traverse S3 passes just south of Fairfield Spring, so the shallow water table here is at or near the land surface. Based on this configureation, we favor the interpretation of the velocity discontinuity as a contact between younger and older basin-fill deposits, rather than a contact between saturated and unsaturated sediments.

In summary, we believe that our seismic-refraction traverses image either a contact between younger, unconsolidated deposits and older, semiconsolidated deposits (our preferred interpretation), or the contact between saturated and unsaturated sediments within Quaternary alluvial-fan and lakebed deposits. The contact is about 20 to 100 feet (6-30 m) below the land surface and slopes gently east. We do not believe that we imaged a fault within the basin-fill deposits that influences the hydrologic connection between the irrigation wells and Fairfield Spring. Our results do not, however, disprove the existence of such a fault below about 200 feet (60 m) deep. Overall the results are, unfortunately, inconclusive as to the nature of the hydrologic connection between Fairfield Spring and the irrigation wells. This topic is discussed further in the section titled, "Fairfield Spring" in the main text.

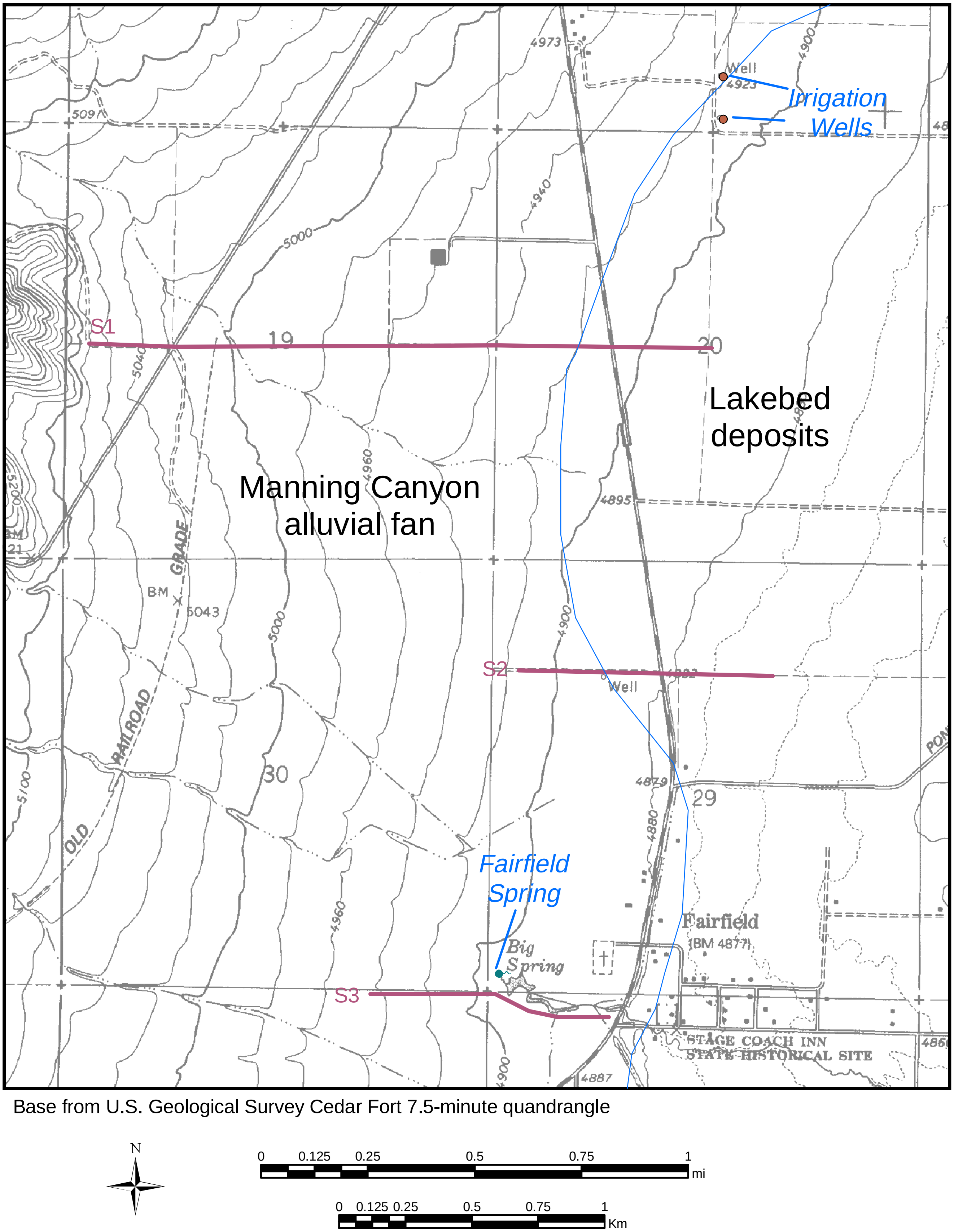

Figure D.1. Locations of seismic-refraction lines, irrigation wells, and Fairfield Spring.

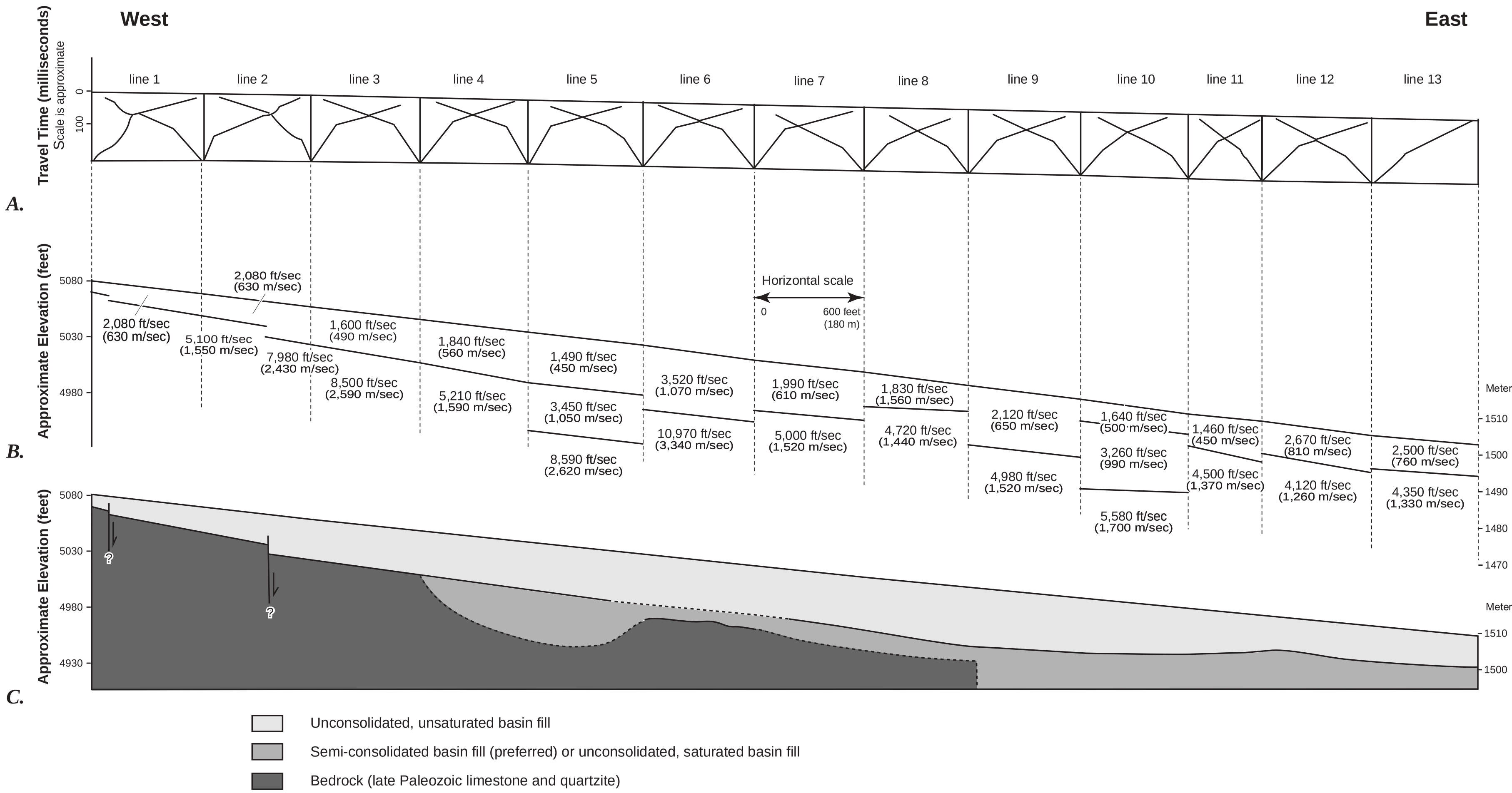

Figure D.2. *Summary of seismic-refraction profile S1 (see figures 17 and D.1 for location).*

A. Schematic travel-time plots for individual refraction lines. Each line consists of 12 receivers spaced 50 feet (15 m) apart for total line length of 600 feet (180 m). The curves on the plots connect the "first breaks" (first observed waveforms) for each receiver. Two travel-time curves are plotted for each line because the source was placed at either end of each geophone array. The velocity of the earth material through which the seismic waves propagate is proportional to the inverse of the slope of the curves. Abrupt slope changes indicate the presence of layers having different seismic-wave velocities.

B. Velocity interpretation of A.

C. Geologic interpretation of B.

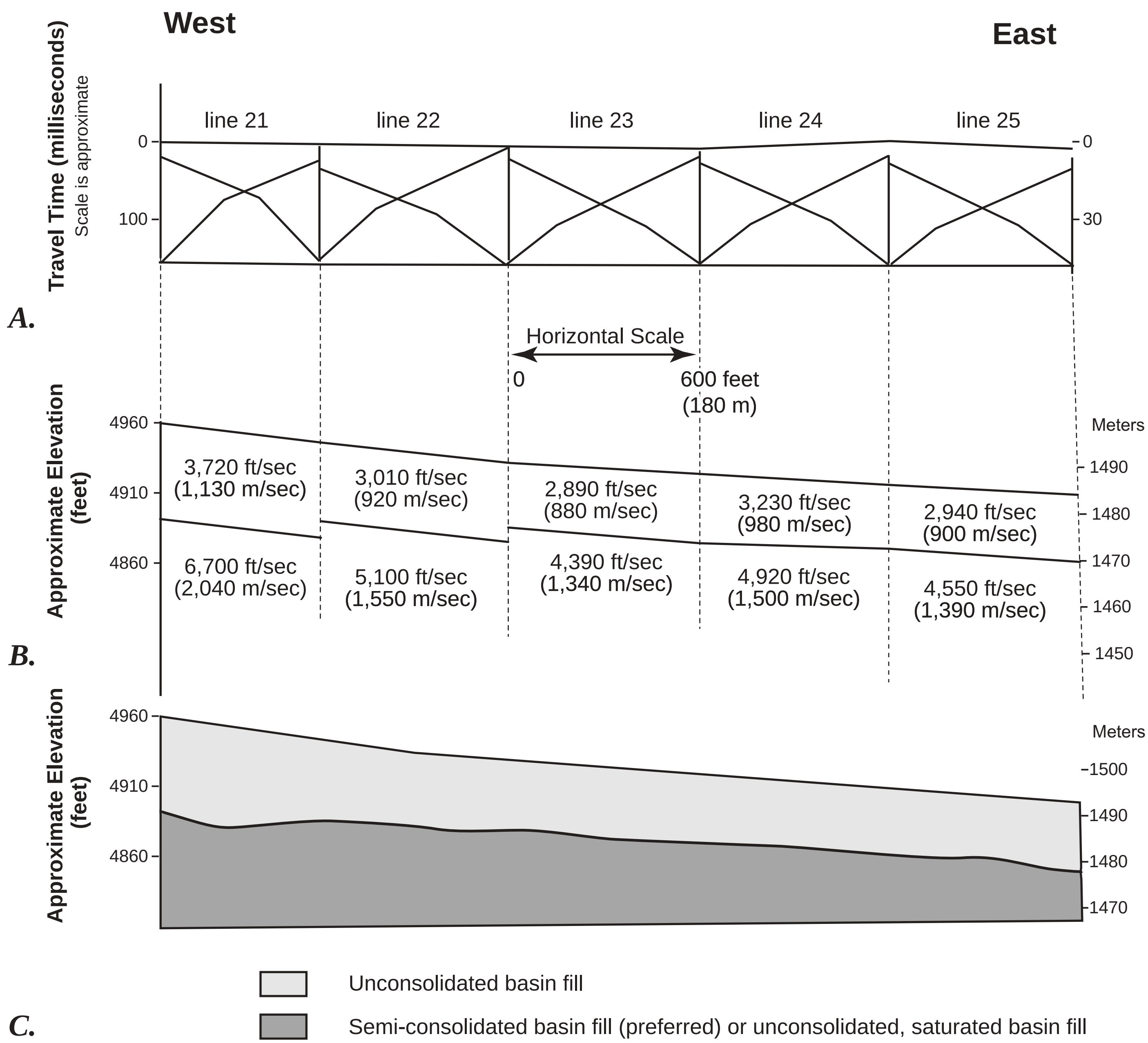

Figure D.3. *Summary of seismic-refraction profile S2 (see figures 17 and D.1 for location).*
A. Schematic travel-time plots for individual refraction lines. Each line consists of 12 receivers spaced 50 feet (15 m) apart for total line length of 600 feet (180 m). The curves on the plots connect the "first breaks" (first observed waveforms) for each receiver. Two travel-time curves are plotted for each line because the source was placed at either end of each geophone array. The velocity of the earth material through which the seismic waves propagate is proportional to the inverse of the slope of the curves. Abrupt slope changes indicate the presence of layers having different seismic-wave velocities.
B. Velocity interpretation of A.
C. Geologic interpretation of B.

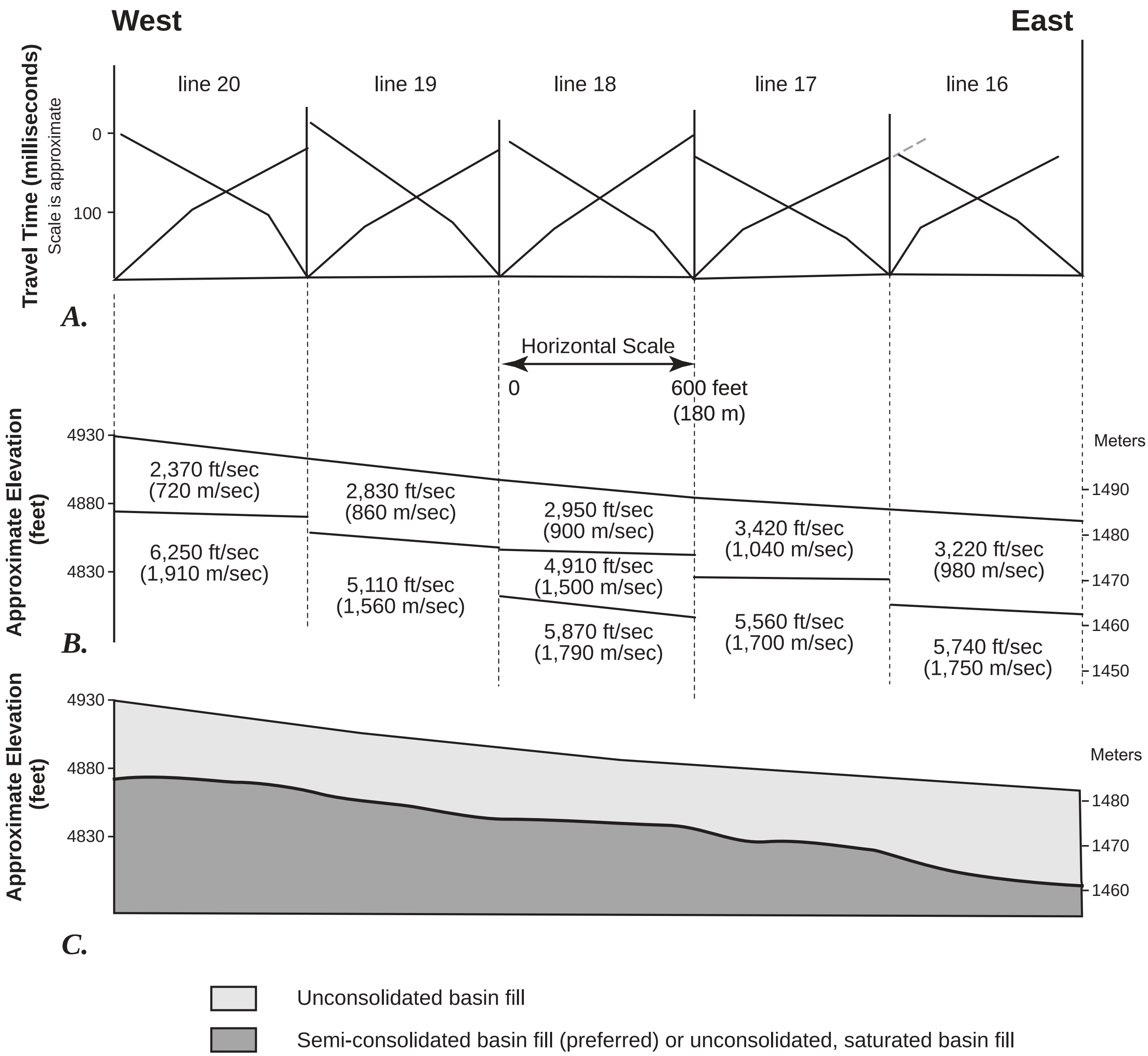

Figure D.4. *Summary of seismic-refraction profile S3 (see figures 17 and D.1 for location).*

A. Schematic travel-time plots for individual refraction lines. Each line consists of 12 receivers spaced 50 feet (15 m) apart for total line length of 600 feet (180 m). The curves on the plots connect the "first breaks" (first observed waveforms) for each receiver. Two travel-time curves are plotted for each line because the source was placed at either end of each geophone array. The velocity of the earth material through which the seismic waves propagate is proportional to the inverse of the slope of the curves. Abrupt slope changes indicate the presence of layers having different seismic-wave velocities.

B. Velocity interpretation of A.

C. Geologic interpretation of B.